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Faculty of Sciences

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PAOLO **RAMONI-PERAZZI**
LÍRIA **ZANDAMELA**
FABIO **ATTORRE**

PROCEEDINGS OF THE SUMMER SCHOOL

MANGROWTH 2024

ECOLOGY AND CONSERVATION OF MANGROVES

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SUMMARY

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Ernesto Matavela	Project Officer (Italian Agency for Development Cooperation – Maputo)

Component - 2

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Paolo Ramoni-Perazzi	Scientific Coordinator and Head of the *Summer School*
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Célia Macamo	Scientific Adviser (Mozambique)
Enrico Nicosia	*Summer School* Coordinator (Italy and Mozambique)
Líria Zandamela	Researcher
Agnes Costa	Researcher
Sérgio Fuca Mapanga	Researcher
Paula Cristina de Carvalho	Administrative Assistant
José Chissiua Dumbo	Management Committee Member and Director of EBMI (UEM)
Osvaldo F. André Loquiha	Management Committee Member
Herminio F. Muiambo	Management Committee Member (former)
Daúd Liace Jamal	Director of the Faculty of Sciences (UEM)
Mariaelisabetta Dessj	Delegated Administrative Responsible (DBA – La Sapienza)

Ida Simeone	Administration (DBA – La Sapienza)
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INTRODUCTION

PAOLO RAMONI-PERAZZI*

The 2024 ManGrowth *Summer School* was built on the solid foundations laid by its inaugural edition in 2023, continuing its mission to promote scientific knowledge and sustainable management of mangrove ecosystems. This second edition took place entirely in Mozambique, beginning on the island of Inhaca and later moving to Maputo. Despite unforeseen challenges, such as disruptions in Maputo due to civil unrest, the *Summer School* provided an invaluable opportunity for international collaboration and hands-on research in one of the most biodiverse and threatened coastal environments in the world.

The 2024 cohort consisted of 14 graduate students, nine Mozambicans and five Italians, selected from a total of 84 applicants. Over four weeks, students participated in fieldwork, lectures, and group projects examining various aspects of mangrove ecology and the socioeconomic dynamics of coastal communities. Despite the difficulties, this approach allowed for greater involvement with the ecosystems of Inhaca, whose mangrove forests continue to provide crucial ecosystem services to the surrounding communities.

Indeed, the island's rich mangrove habitats once again became a living laboratory for various short-term research projects, supervised by

* Scientific Coordinator – Project ManGrowth; General Coordinator – Summer School.

an international team of experts and offering participants the opportunity to work alongside academics with extensive experience in their fields.

Mangroves are not just biodiversity hotspots: they are complex systems that connect terrestrial and marine environments and meet a wide range of human and ecological needs. Consequently, the thematic diversity of the research projects compiled here reflects the importance of a holistic approach to studying mangroves. The work of the students has advanced our understanding of the ecological functions of mangroves, their socioeconomic importance, and their critical role in mitigating climate change.

The reports presented in this volume are the preliminary results of the participants' research. Due to the limited time and logistical challenges faced during the fieldwork, these findings should be considered initial steps: valuable contributions to the ongoing scientific dialogue, but far from definitive conclusions. However, the quality of the work presented here reflects the significant effort, dedication, and scientific curiosity of the excellent international lecturing team and participating students.

In addition to academic and scientific objectives, the 2024 *Summer School* continued to emphasize the importance of intercultural and interdisciplinary collaboration. The international mix of Mozambican and Italian students provided a rich platform for knowledge exchange, allowing participants to learn from each other's perspectives and experiences. The collaborative projects were designed not only to deepen scientific knowledge, but also to create lasting networks of environmental professionals, fostering an ongoing commitment to mangrove conservation that extends beyond the duration of the program.

As I reflect on the experience, I think back on the hard work and perseverance of the faculty and students, and I am reminded that this *Summer School* is about more than research: it is about cultivating a lasting sense of responsibility toward the environment, fostering a global community of scholars, and empowering future generations to protect the biodiversity and ecosystems that are crucial to the health of our planet.

Maputo, September 20, 2025

Similar to the growth our students experienced, these propagules of red mangrove (Rhizophora mucronata), with their one-of-a-kind ability to sprout while still attached, are ready to start their own journey, showing the curiosity and teamwork that developed during our coastal research program (photo by Paolo Ramoni-Perazzi).

ACKNOWLEDGMENTS

The editors of these *Proceedings* wish to express our deepest gratitude to all individuals and institutions who contributed significantly to the success of the ManGrowth *Summer School* 2024. In particular, without following a specific order, we are grateful to:

The Italian Agency for Development Cooperation for the generous financial support to the ManGrowth Project, which has played a crucial role in the successful implementation of the project's activities and has ultimately made the organization of the *Summer Schools* possible.

Our heartfelt thanks go to our team. Lídia Rosa Manjate, in her role as administrator, has been a pivotal figure essential to the success of our Project. Enrico Nicosia provided invaluable support both throughout the bureaucratic processes at La Sapienza and during the *Summer School*. The activities of the *Summer School* 2024 also benefited from the support of Sérgio Fuca Mapanga, Líria Zandamela and Paula Cristina de Carvalho.

The professors at Inhaca were the backbone of the program, providing dedication and expertise throughout the intensive teaching: Alejandra Soto Werschitz (Instituto de Ecología AC, Mexico), Carine Bourgeois (USDA Forest Service International Programs and Trade, Congo), Giampaolo Orlandoni-Merli (Universidad de Los Andes, Venezuela), Josefa Ramoni-Perazzi (Universidad Industrial de Santander, Colombia), Monika Quinones Winder (Stockholm University, Sweden), Pierfrancesco Moretti (Consiglio Nazionale delle Ricerche, Italy), and Vilma Antonio Machava (Universidade Eduardo Mondlane, Mozambique).

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Several collaborators and Departments of the Eduardo Mondlane University played key roles in the realization of this *Summer School*. Prof. Célia Macamo from the Department of Biological Sciences, who in addition to participating as a professor, has made great contributions to the Project as our academic referent. Prof. Daud Liace Jamal, Director of the Faculty of Science, has been a key partner, providing invaluable support. In Maputo, the students benefited from practical lessons on methods for analyzing mangrove soils, organized/delivered by Professors Armindo Cambule, António Machava, and Ernestina Atanázio Macamo from the Department of Rural Engineering at Eduardo Mondlane University's Faculty of Agronomy and Forestry Engineering. Special acknowledgment goes to the Cooperation Office team, in particular Prof. Manuel Luis Chenene, Prof. Silva Muchanga, Ângela Fernandes, Nelsa Matusse, Ana Pedro Sitoe, and Claudio Casimiro Moca for their exceptional performance in the overall logistics and procurement of migration support in Mozambique.

Among the UEM facilities, the Inhaca Marine Biology Station deserves special recognition for providing the infrastructure and resources that made the *Summer School* phase on Inhaca Island possible. The logistical and administrative support of its Director, Prof. José Chissiua Dumbo, was particularly decisive. We are also grateful to Graça Cambule for her valuable assistance, and to Chico Manuel Filipe, Alberto Nhaca, Almerinda Neto Singa, Ebifânio Rosário João, and Mito Nhaca, whose contributions were fundamental to the success of the fieldwork.

STVDIVM VRBIS

In the case of Sapienza-Università di Roma, several departments and individuals played a fundamental role in the realization of this *Summer School*. In the Department of Environmental Biology, we had the valuable administrative support of Mariaelisabetta Dessj and Ida Simeone. We received administrative support from Mariadaniela Salvati, Anna Argentieri, Francesca Romana Longo, Tommaso Niccolò Fiammeri, and Valeria Salvadori.

Encanto
Catering ,SU, Lda
gastronomico

Encanto Gastronómico, represented by Kassia Marco, deserves special recognition for their outstanding contribution at Inhaca, providing healthy, and high-quality meals served with remarkable care and warmth.

Likewise, the numerous transfers between Maputo and Inhaca were made possible through the support of Márcio Sousa and his Bussola.

The special ceremony of the *Summer School*, held during the visit of representatives from the Italian Embassy in Maputo and the Italian Agency for Development Cooperation, was kindly catered for by Oswaldo José Matias Lista from Pioneira Alimentar Moçambicana.

Very importantly, we would like to express our deep gratitude to our 14 students for the effort, warmth, good humor, and ideas with which they enriched this *Summer School*. To Augusto Nhampossa, Aura Rapino, Clotilde Nhancale, Davide Crescenzi, Delcio Munissa, Gerson Gonca, Geúsia Mazuze, Lavinia Scepi, Márcia Mucavele, Marta Polizzi, Noemi Bernardini, Nordine Camale, Salvador Nanvonamuquitxo, and Zaira Macheve, we sincerely thank you for your dedication and active participation, which greatly contributed to the success of our *Summer School*. Your enthusiasm and input were instrumental in making this educational experience both enriching and memorable.

Finally, we would like to thank the people of Inhaca for sharing with us a glimpse into their lives in this incredible paradise.

THE AUTHORS OF THESE MANUSCRIPTS: OUR PROFESSORS

Carine Bourgeois. Belgium citizen, raised in Lubumbashi, Congo, where part of her family originated from. At the end of her Master's in Biology at the Free University of Brussels, she completed a thesis on the ecophysiology of mangroves in the Province of Guangdong, China. She then achieved a PhD at the Auckland University of Technology on nutrient dynamics and ecophysiology of temperate and semi-arid mangroves in New Zealand and New Caledonia, respectively. Carine has also been involved in diverse research projects, including the spatial distribution of coral reefs in Okinawa, Japan; the implementation of a Jatropha curcas plantation in the Central African Republic to produce biofuel and soap, thus preventing deforestation while empowering local communities with new sources of incomes; and the installation of an eddy covariance Tower in New Zealand. Since 2021, Carine has been working as a researcher on several projects in the Sustainable Wetlands Adaptation and Mitigation Program (SWAMP, USDA Forest Service, CIFOR). She currently focuses on diverse aspects of mangrove restoration, including the restoration of carbon stocks in planted mangrove forests worldwide.

Célia Macamo. A marine biologist and lecturer at Eduardo Mondlane University in Maputo since 2008. Currently serving as the Director of the Masters Course on Biology and Ecology of Conservation, her research interests span ecology and management of mangrove forests, as well as botanic components of various marine and terrestrial ecosystems. With a focus on mangrove ecology, conservation, and management, she has also delved into socio-economics, restoration, and carbon assessments. Beyond academia, she provides environmental advisory services to government and private institutions and conducts environmental assessments and monitoring for development projects in coastal and terrestrial habitats. Her contributions extend to peer-reviewed journals, books, technical and scientific reports, as well as documentaries and scientific meetings. Furthermore,

Célia Macamo holds positions as the country representative for the Western Indian Ocean Marine Science Association, a member of the Mangrove Capital Africa Advisory Group, and a Focal Point for the Western Indian Ocean Mangrove Network.

Giampaolo Orlandoni-Merli. a Senior Researcher at Minciencias-Colombia, is a distinguished academic and Full Professor at the Universidad de Los Andes (ULA) in Venezuela, and Universidad Industrial de Santander in Colombia. With expertise spanning economics, econometrics, and environmental economics, he earned his degrees from renowned institutions like Iowa State University and Cornell University. His contributions include impactful research in environmental economics, climate variability, and project evaluation. Recognized for his excellence by esteemed bodies such as the American Economic Association and the Venezuelan Ministry of Sciences, Dr. Orlandoni-Merli has also held administrative positions, directing the Institute of Applied Statistics at ULA and coordinating its Applied Statistics Master's program. Through collaborative projects with organizations like the Petroleum of Venezuela and the World Bank, he has made significant strides in areas such as environmental impact assessments and regional development initiatives. With a wealth of experience and a dedication to academic excellence, he continues to shape the field of economics.

Alejandra Soto-Werschitz. She has over 10 years of experience in research, teaching, university outreach, and public science communication across Mexico, Venezuela, and Brazil. She has been recognized for her distinguished academic career, contributions to science communication projects, and as a member of the National System of Researchers (SNI) by CONAHCYT-Mexico. She holds a Bachelor's degree in Biology from the National Autonomous University of Mexico (1994), a Master of Science in Wildlife Management from the Institute of Ecology AC, Mexico (2000), and a Ph.D. in Applied Ecology with a focus on fragmented ecosystems and agroecosystems from the Federal University of Lavras, Brazil. Currently, she is a member of the Academic Group of Ecology and Faunal Diversity at the University of Querétaro, Mexico, as a Scientist-Extension Specialist. Her projects cover areas such as ecology, animal ecology, biodiversity conservation, climate change, occupancy models, reproductive animal behavior, and the impacts of human intervention, fragmentation, and habitat loss on mammal diversity in different ecosystems. Her work has established strong

connections between public universities, civil society, government and non-governmental organizations, and communities, all for the benefit of wildlife conservation.

Josefa Ramoni-Perazzi. An Economist (Venezuela), magister in Statistics (Venezuela), Ph.D. in Economics (USA). After retiring from the Universidad de Los Andes in Venezuela, she moved to the Universidad Industrial de Santander in Colombia, where she works as a full professor at the College of Economics and Administration. Classified as a Senior Researcher by the Colombian Ministry of Education, she has multiple publications in applied statistics and economics. Professor Ramoni-Perazzi has been actively involved in several environmental valuation projects in Venezuela, including the construction of environmental satellite accounts in her country.

Monika Quinones Winder. Monika Winder is a Professor of Marine Pelagic Ecology at Stockholm University's Department of Ecology, Environment, and Plant Sciences. Her research investigates plankton dynamics, food web interactions, and climate change effects on aquatic ecosystems, with a focus on the Baltic Sea. She earned her Ph.D. in Natural Sciences from ETH Zurich in 2002, a Habilitation from Christian-Albrechts-University Kiel in 2012, and was appointed Docent at Stockholm University in 2013. Winder has secured significant funding, including from the Swedish Research Council, for projects like "Drivers of protist parasites in plankton food webs." Recognized as a Highly Cited Researcher in 2020, she has 87 peer-reviewed publications and an h-index of 39. Winder teaches master's and Ph.D. courses, supervises students, and contributes to public outreach through media and talks. She serves on the editorial board of Journal of Plankton Research.

Paolo Ramoni-Perazzi. – A former researcher and professor at the University of Los Andes, Venezuela, affiliated with the Department of Biology and the Simulation and Models Center, from 1992 to 2017. Paolo is currently serving as the Scientific Coordinator for the ManGrowth Project. With direct field experience in various biodiversity hotspots in Latin America, Paolo has been interested in the natural history and conservation of tropical birds and mammals, although he has experience in other regions and topics, such as climatology. Currently, Paolo is focused on the ecology and conservation of mangroves in Mozambique. Paolo holds a Bachelor's degree in Biology (University of

Los Andes, Venezuela), a Master's degree in Systematics (Institute of Ecology AC, Mexico), another Master's in Modeling and Simulation of Systems (University of Los Andes, Venezuela), and a doctorate in Applied Ecology (Federal University of Lavras, Brazil). Paolo is a co-author of over 50 peer-reviewed publications and presentations at conferences, some of which have been cited by prominent mass media outlets such as The New York Times. Paolo's teaching experience spans from primary education to postgraduate level, including diverse groups such as rural communities. He has taught or participated in teaching courses and subjects focused on different topics related to biology and ecology at both undergraduate and postgraduate levels in institutions in Venezuela, Mexico, Brazil, and Mozambique.

Pier Francesco Moretti. Pier Francesco is a physicist with two PhDs, more than 90 international publications in helioseismology, material, marine, and political sciences. His research skills are mainly focused on spectroscopy, data analysis, and innovative technologies. He has been involved in many international projects and Governmental Boards, working also in the USA, Antarctica, Austria, and Belgium. He has been responsible for the Office for the International Activities of the CNR Department of Earth and Environment and was appointed also as a scientific officer at the CNR Liaison Office in Brussels for the support of policy decisions. He has been vice-chair of the Research Working Party of the EU Competitiveness Council during the Italian Presidency of the European Union. He designed and coordinates an innovative training course for decision and negotiation processes (school4sid.cnr.it) and a foresight initiative for the development of a new generation of materials. Recently, he proposed an observing strategy and an experimental setup for the acquisition and analysis of underwater acoustic signals and their role in the equilibrium of the ecosystems. See also pierfrancescomoretti.eu

The people of Inhaca, as seen in this photo of a group of women carrying mollusks and shellfish from their daily harvest in the Noge mangroves, joined the other instructors of this Summer School in generously sharing with students what it means to live and survive in this paradise. (photo by Paolo Ramoni-Perazzi).

THE AUTHORS OF THESE MANUSCRIPTS: OUR STUDENTS

Augusto Júnior Nhampossa. Augusto holds a degree in Environmental Science and is pursuing a Master's in Conservation Biology and Ecology. He also has an MDA in Project Management, with training in Leadership and Communication from Harvard University and mangrove restoration by the Mangrove Action Project. Currently enrolled in the Wildlife Conservation Network Career Program 2024, Augusto specializes in coral reef and mangrove management as a coastal and marine conservation junior expert. As a project manager at Associação Natura Moçambique, he supports socio-ecological transformation in vulnerable coastal regions by fostering leadership, critical thinking, and co-creation skills. Augusto is dedicated to environmental education and ocean literacy, empowering children and communities. A certified Reef Check ecological diver, he actively participates in cleanup projects and creates underwater videos. In 2019, he joined the first marine expedition from Pomene to São Sebastião, Inhambane.

Aura Rapino. Aura holds a Bachelor's degree in Biology, during which her thesis focused on behavioral experiments with zebrafish (*Danio rerio*, Cyprinidae). She is pursuing a Master's in Ecobiology focusing on marine ecosystems at La Sapienza University in Rome. Aura has a strong passion for environmental conservation and the study of animal behavior. Her academic interests are centered on the behavior of marine animals and the sustainable management of coastal environments. Aura has participated in various courses, enhancing her understanding of ecological principles and their practical applications. Her commitment to protecting natural habitats and her curiosity about the natural world continue to guide her academic and professional endeavors.

Clotilde Fátima Nhancale. A Forestry Engineer with a master's in Conservation Biology from the Gorongosa National Park Bioeducation Program. She is a researcher at the Mozambican Agricultural Research Institute, focusing on ecology and forest management. Clotilde researches above- and below-ground plant biomass in Mozambique and South Africa to develop solutions for carbon sequestration in savannah ecosystems and enhance the livelihoods of communities near protected areas. To further her expertise, Clotilde attended a training in Dendrochronology in Zambia, where she used tree rings to determine the age of trees and understand past climates, building climate trends as tools for adapting to climate change. She is also deeply engaged in climate justice, having participated in the 4th Symposium on Climate Justice and the fourth cohort of the Nairobi *Summer School* on Climate Justice. These experiences provided her with a platform to collaborate with international actors and address the pressing challenges of climate change that Africa faces. Clotilde is committed to developing her technical and professional skills, focusing on understanding the impacts of global changes on biodiversity and people's lifestyles. She is particularly interested in how forests can contribute to addressing these challenges, especially within the context of Mozambique's current global climate scenarios.

Davide Crescenzi. With a Bachelor's degree in environmental science from the University of Rome "La Sapienza", his thesis delved into the evolution of the "Calderone" glacier from the second industrial revolution to 2023. He is attending a Master's degree course in Environmental Monitoring and Redevelopment from the same institution. Davide completed various traineeships including monitoring microorganisms in aquatic environments through chemical and biological analyses at the IRSA-CNR, and monitoring of pollinators in permanent plots around "Bullicante" Lake in Rome in collaboration with the University of Rome "La Sapienza". Fluent in Italian and English, he possesses skills in QGIS and Microsoft Office tools. Davide is passionate about environmental conservation and the monitoring of endangered ecosystems.

Délcio António Munissa. Délcio is currently pursuing a Master's degree in Conservation Biology and Ecology at Eduardo Mondlane University, where he also earned his bachelor's degree in Forestry Engineering. He worked as a monitor on a community-based restoration project with the Éden Reforestation Project in the Mecuburi Reserve, Nampula Province. Proficient in both Portuguese and English, Délcio has received professional training in data analysis using tools such as R, QGIS, ArcGIS, and others. With his strong academic background, practical experience, and eagerness to learn, Délcio is well-prepared to make meaningful contributions to conservation efforts.

Gerson Gonca. A Master's student in Applied Ecology at Lúrio University and holds a Bachelor's degree in Aquaculture Engineering. Currently, he is part of the Internship Programme of the Mozambique Conservation Leadership Programme (PLCM), promoted by BioFund, developing skills in environmental conservation, community leadership, and biodiversity project management. He completed the Training Programme on Ocean Governance for Africa 2024 (International Ocean Institute, Cape Town), strengthening his knowledge in marine policies, blue economy, conservation, and small-scale fisheries management, and was recognised for producing a policy brief on sustainable fisheries in West Africa. He also took part in the Fourth Virtual Cohort Programme on Climate Change (Climate College Hub, Revamp Rave Network, 2025), deepening his understanding of climate science, policy, and sustainable development over 14 weeks of sessions led by international experts. He participated in the Global Volunteer Project in Dar es Salaam facilitated by AIESEC Mozambique and Tanzania, contributing to SDG 15 - Life on Land by empowering communities to protect natural habitats and biodiversity, while strengthening leadership, intercultural communication, and environmental education skills. He is proficient in Portuguese, English, and Changana, with experience in Microsoft Office, QGIS, and ArcGIS. He is deeply passionate about biodiversity conservation and the protection of marine and coastal ecosystems.

Geúsia Leonardo Mazuze. Geusia holds a degree in Forestry Engineering from the Faculty of Agronomy and Forestry Engineering and is currently pursuing a master's degree in Conservation Biology and Ecology at the Faculty of Science. During her academic and professional career, she had the opportunity to work on the EBA-Project (Building Resilience in the Coastal Zone through Ecosystem-Based Approaches to Adaptation in the Greater Maputo Region) in the baseline study. She also worked as an intern assistant in the Oliver Tambo Africa Research Chair Initiative (ORTARChI) program and currently has a scholarship from the program for her master's degree. Geusia has knowledge of software such as QGIS, RStudio, and SPSS.

Lavinia Scepi. Holding a Bachelor's degree in Natural Sciences from the University of Rome 'La Sapienza', Lavinia is currently pursuing a Master's degree in Environmental Monitoring and Redevelopment at the same institution. She has completed various traineeships focused on monitoring projects, such as pollinator monitoring at Bulicante Lake in Rome, microplastics monitoring, and microorganism monitoring in aquatic environments at the IRSA-CNR in Montelibretti. Fluent in Italian and English, she also speaks French and German. She is particularly interested in redevelopment and conservation projects involving delicate environments.

Márcia Alberto Mucavele. She holds a degree in Fisheries Production with a specialization in Aquaculture from Eduardo Mondlane University and is currently pursuing a Master's degree in Conservation Biology and Ecology at the same institution. She was previously part of the Leadership Program for Conservation of Mozambique (PLCM) under the Foundation for Biodiversity Conservation (Biofund), where she worked with the main aquatic ecosystems in Maputo National Park. She is currently conducting research on the effects of climate change on freshwater aquatic ecosystems as part of the Oliver Tambo Chair Project at the Faculty of Agronomy and Forestry Engineering, focusing on climate change adaptation in arid and semi-arid regions of the Limpopo Corridor.

Marta Polizzi. A biologist specializing in bat ecology. She graduated with honors in Ecobiology from Sapienza University, where her thesis focused on the physiological and behavioral impacts of climate change on a population of riparian bats in central Italy. Her interest in bioacoustics led her to become proficient in software for acoustic analysis, including R, QGIS, SNAP, and the Office Package. During her master's degree, Marta worked extensively in environmental education, serving as a park guide in nature reserves, at the Rome Zoo, and as a tutor for university students in Zoology and Geological Sciences. She also became involved in grassroots movements aimed at the reappropriation of natural areas and collaborated with various associations. Recently, Marta has participated in citizen science projects, gaining experience in social engagement and participatory monitoring activities. Through her combined professional and volunteer experiences, she has developed practical fieldwork skills and is committed to making a meaningful contribution to conservation biology.

Noemi Bernardini. She holds a bachelor's degree in Natural Sciences from the University of Florence and continued her studies in Biology and Terrestrial Conservation at the University of Rome La Sapienza. She completed an internship focused on the integration and drafting of the NISECI index for 20 river areas in Tuscany and was involved in the collection and sampling of two fish species, followed by bacterial analysis of 16S DNA in the microbiology laboratories of Sesto Fiorentino. She is also interested in development projects and international cooperation.

Nordine António Nunes Camale. A biologist whose research and environmental conservation interests focus on mangrove ecology, management, and the restoration of mangrove ecosystems. His passion for environmental conservation led him to participate in the PRONTIDAO 2022 Project with Lúrio University, where he contributed to the recovery of mangroves in the districts of Metuge and Mecufi in Mozambique. He is currently a technician in coastal natural resource management and mangrove ecosystem recovery at Istituto Oikos, where he has continued to contribute to mangrove recovery efforts in the Metuge district of Mozambique. Proficient in Portuguese, English, Macua, and Kimwani, his language skills enhance communication. With a practical combination of academic achievements and hands-on environmental projects, he is well-positioned to make significant contributions at the intersection of biology and conservation efforts.

Salvador José António Nanvonamuquitxo. Holding a Master's degree in Forestry Engineering from the Faculty of Agronomic and Forestry at Zambéze University (UniZambéze), Salvador currently works as a lecturer in the Faculty of Natural Sciences at Lúrio University (UniLúrio). He is also involved in mangrove restoration projects in northern Mozambique (PRO-RESILIENCE, PRONTIDÃO, and ETHAKA projects), with a particular focus on the districts of Mecufi and Metuge in Cabo Delgado. Salvador's interests include mangrove ecology and the resilience of communities to the impacts of climate change.

Zaira Valgi Macheve. A junior researcher in Ecology and Biodiversity Conservation, with a licentiate degree in Ecology and Terrestrial Biodiversity Conservation from Eduardo Mondlane University. Zaira gained practical experience as an intern at the Ministério da Terra e Ambiente (MTA), where she focused on biodiversity offsets and Environmental Impact Assessments (AIA), topics she also explored in her monograph. Zaira participated in botanical fieldwork in Gorongosa National Park, contributing to the Flora of Mozambique. Additionally, she interned at the Instituto de Investigação Agrária de Moçambique (IIAM), where she worked on species identification, the digitization of the National Herbarium, and supported technicians in various projects. As a passionate Climate Justice advocate, Zaira volunteers with NGOs and community initiatives in Mozambique and Pakistan. Currently, Zaira is working as a Junior Ecologist on the COREBIOM Project, where she is gaining experience in tools like Google Earth Engine (GEE), Quantum GIS, and R, contributing to biodiversity conservation efforts in Mozambique.

Attending lectures, conducting field studies, interacting with local communities, analyzing samples in the laboratory, processing data and statistics, and presenting results through oral expositions and written reports (compiled in the present Proceedings), the Summer School provides students with a comprehensive experience of real-world academic life. (photos by Enrico Nicosia).

BIOACOUSTICS IN MANGROVE ECOSYSTEMS
EXPLORING THE POTENTIAL OF A BIOACOUSTIC MONITORING STATION IN THE MANGROVE ECOSYSTEM OF INHACA

AUGUSTO NHAMPOSSA, AURA RAPINO, CLOTILDE NHANCALE, MARTA POLIZZI
LAVINIA SCEPI, ZAIRA MACHEVE
(SUPERVISOR: PIER FRANCESCO MORETTI)

Abstract: Mangrove ecosystems host diverse biological communities and play a critical role in coastal resilience. Yet they remain understudied due to logistical challenges in biodiversity monitoring. We aimed to evaluate the feasibility and performance of a low-cost, multisensory passive acoustic monitoring (PAM) system for capturing soundscapes in mangrove environments. To achieve this, we deployed two acoustic monitoring stations on Inhaca Island, Mozambique, in October 2024. We selected deployment sites based on a combination of local ecological knowledge and landscape analysis, optimizing for both accessibility and environmental representativeness. Each station enabled simultaneous acoustic recordings in air, water, and soil using integrated low-cost sensors and locally available materials. We collected data across different times of day and environmental media, capturing a wide range of biophonic, geophonic, and anthropophonic sounds. Our preliminary analysis revealed spatial and temporal variability in acoustic activity, highlighting the ecological richness of the mangrove soundscape. We identified both strengths and limitations in our monitoring setup and propose targeted improvements for future iterations. These results demonstrate the potential of PAM as an accessible and minimally invasive tool for long-term biodiversity monitoring in mangrove ecosystems, and are useful for obtaining a wide variety of information about biodiversity.

Keywords: Bioacoustics, Biodiversity, Mangrove, Marine Habitats, Passive Acoustic Monitoring.

I. Introduction

Mangrove ecosystems, usually found in tropical and subtropical coastal areas, are critical habitats that provide numerous ecological services, such as coastal protection and carbon sequestration, serve as nurseries and shelter for various marine species, are fundamental for the maintenance of the coastal line and constitute a vital protection from extreme meteorological events and tides. People living on the islands with mangroves rely on mangroves for fishing activities and extraction of firewood, charcoal, and timber to build houses, furniture, and fishing gear, so many ecosystem services are related to mangroves' occurrence in tropical and subtropical areas (Carrasquilla-Henao & Juanes, 2017).

The island of Inhaca in Maputo Bay harbors extensive mangroves, with seven different species distributed according to the characteristics of the coast. Research in Maputo Bay mangroves has increased in the past 20 years, mainly targeting the distribution and abundance of faunal elements and biological components of the mangrove ecosystem and its resources (Frosi et al., 2025).

Due to their importance in providing goods and services for human coastal populations, Inhaca's mangrove forests are becoming a nature-based model system in research activities in that area. For example, aspects such as tides, diel and semilunar periods have been studied in some detail at Inhaca Island mangroves, as they modulate biological activities and the whole ecology of mangroves (Bandeira et al., 2014; Obrist et al., 2010).

A. *Bioacoustics and its importance in ecology*

Diverse organisms, including crustaceans, arachnids, insects, fish, amphibians, reptiles, birds and mammals, produce species-specific acoustic signals during their daily activities (Blumstein et al., 2011; Obrist et al., 2010). Such signals can be recorded to determine the presence of various animal species and many aspects of their ecology and behavior (Obrist et al., 2010). Animal acoustic signals serve communication purposes and most often contain species-specific information and individual information that receivers can use, making bioacoustics

perfectly suitable to monitor biodiversity (Bradbury & Vehrencamp, 2011; Madhusudhana et al., 2021).

Understanding animal abundance is a critical component of wildlife conservation (O'Brien, 2011), and passive acoustic monitoring (PAM) methods are used for monitoring and studying various soniferous species. By exploring these sounds and temporal comparisons of acoustic data, we can gain valuable insights into species' behavior, environmental stressors, and the effects of seasonal changes, which are crucial for informed conservation efforts.

Soundscape ecology is a rapidly growing field with approximately 93% of all scientific articles on this topic being published since 2010 (Lindseth & Lobel, 2018). Current acoustic technology is also advancing rapidly, enabling new devices with voluminous data storage and automatic signal detection to define sounds. Considering the existing literature, bioacoustics elements have been largely applied to monitor aerial, terrestrial, and aquatic organisms. The exploration of sound using underground microphones remains largely unstudied.

Water acoustic research has been concentrated on single-species studies, and field surveys of waterbody soundscapes have scarcely been undertaken. As a result, knowledge of both overall soundscapes, and the sounds produced by freshwater organisms such as macroinvertebrates, is lacking (Rountree et al., 2020). Despite these large gaps in understanding the identification of many species and the functioning of the systems as a whole, the few studies that have employed eco-acoustic methods, without the need for species identification, have revealed differences between sites, reflecting variability in both biological communities and environmental factors (Putland & Mensinger, 2020; van der Lee et al., 2020).

Soil bioacoustics is an emerging field with considerable potential to improve soil biodiversity monitoring and 'soil health' diagnostics. Indeed, early studies suggest soil eco-acoustics can be successfully applied in various ecosystems (e.g., grasslands, temperate, tropical, and arid forests) and land uses (e.g., agriculture, viticulture, natural and restored ecosystems). Given the low cost, minimal intrusiveness, and effectiveness in supporting soil biodiversity assessments and biosecurity risks (Robinson et al., 2024), this approach can provide valuable

information alongside recordings made in the air and underwater, for which a significantly greater amount of data is available in the scientific literature.

Soil bioacoustics has the potential to support restoration biodiversity assessments, providing minimally intrusive, cost-effective, and rapid surveying and monitoring tools. The methods are also relatively simple to learn and apply (Robinson et al., 2023). These tools are still unexplored in tropical regions, even though tropical forests constitute the most biodiverse habitat in the world and the most threatened by human impact. Anthropological impacts such as forest disturbance have already been shown to negatively impact soil fauna, although the temporal and spatial dimensions of such impacts are poorly understood (Robinson et al., 2024).

B. *Bioacoustics in mangrove ecosystems*

Studies in other nearshore vegetated ecosystems may provide insights to guide mangrove research. Recently, several investigations tested the detection performance of active and passive acoustic telemetry in wetland environments with submerged aquatic vegetation in lakes and found that acoustic transmitters can be effectively used in vegetated shallow-water environments (Kanno et al., 2025).

By comparing soundscapes between three shallow benthic habitats close to the coast of the Florida Keys (mangroves, seagrass, hard bottoms), Butler et al. (2016) demonstrated that tropical coastal habitats have unique soundscapes that are diminished by habitat degradation but can be re-established by habitat restoration. Of these, the mangrove shows higher levels of soundscape spectra, both at midday and at dusk, during new or full moons. Low-frequency sounds, probably fish calls in the ~300 Hz range, were more commonly heard in the mangroves during full moons at dusk.

Research on mangrove ecosystems remains limited. However, existing studies have demonstrated that bioacoustics is an effective tool for tracking animal movements and gaining insights into the diverse fauna utilizing these habitats. Deploying bioacoustics equipment across different mediums (air, water, and soil) within the mangrove ecosystems

of Inhaca Island could provide a comprehensive means of capturing the soundscape produced by terrestrial and aquatic species across tidal cycles. This method is particularly valuable for detecting cryptic or elusive species and serves as a critical approach for assessing biodiversity and evaluating the overall health of the ecosystem.

II. Objectives

A. *General*

To test the potential of a bioacoustics monitoring station for discovering different sounds in the mangrove ecosystem of Inhaca.

B. *Specific*

- To explore sounds in different locations in the mangrove ecosystem.
- To compare acoustic data across various times of day and in air, water, and soil.
- To evaluate the pros and cons of bioacoustics equipment.

III. Rationale

The installation of bioacoustics monitoring systems within the mangrove ecosystem on Inhaca Island is a fundamental starting point for conducting a comprehensive assessment of the region's biodiversity. By systematically capturing and analyzing acoustic signals from multiple locations, it is possible to detect species that are elusive or difficult to observe through conventional visual methods, enabling non-invasive monitoring of their presence. Acoustic sampling across various mangrove zones will facilitate the identification of areas with heightened biological activity, offering insights into interspecific interactions and ecosystem dynamics.

Moreover, temporal comparisons of acoustic data, recorded at different times of day and across seasonal cycles, are essential for elucidating

biological and functional patterns of animal behavior (Maeder et al., 2022). This temporal analysis provides a deeper understanding of species' responses to environmental factors, such as tidal cycles, seasonal variations in weather, and anthropogenic disturbances. These findings will be pivotal in assessing the ecological integrity of the mangrove ecosystem, thereby informing the design of more targeted and effective conservation and management strategies to preserve its biodiversity.

IV. Materials and methods

A. *Description of the study area*

Inhaca Island, located in the Indian Ocean approximately 32 km east of Maputo, the capital city of Mozambique, lies at 26 °S latitude and 33 °E longitude (Figure 1). The island covers an area of 40 km^2 and extends about 12.5 km from its northernmost point (Ponta Mazondue) to its southernmost point (Ponta Torres), with a relatively narrow width of just over 1 km in some areas (Moreira, 2005).

According to Pereira & Nascimento (2016), the climate of Inhaca is moderately humid tropical, characterized by two distinct seasons: a cool, dry season from April to September and a hot, humid season from October to March. During the warmest and wettest months, temperatures range from 26.2 °C to 26.3 °C, with rainfall levels of 135.9 mm and 143.9 mm, respectively. The lowest recorded monthly rainfall is 23.7 mm, coinciding with a temperature of 19.6 °C. The prevailing wind direction is southwest, although from October to January, winds from the northeast dominate. Relative humidity peaks at 82.1%, while evaporation averages approximately 100 mm/month, showing moderate variation.

Inhaca supports diverse habitats, including coastal forests, coastal scrubs, woodlands, floodplain vegetation, and pioneer vegetation. Pioneer vegetation, dominated by succulent herbaceous species, forms a dense ground cover above the high tide line. These plants thrive on loose, sandy soils that are dry, low in organic matter, highly saline, and exposed to strong ocean winds. Floodplain vegetation occupies 17.5%

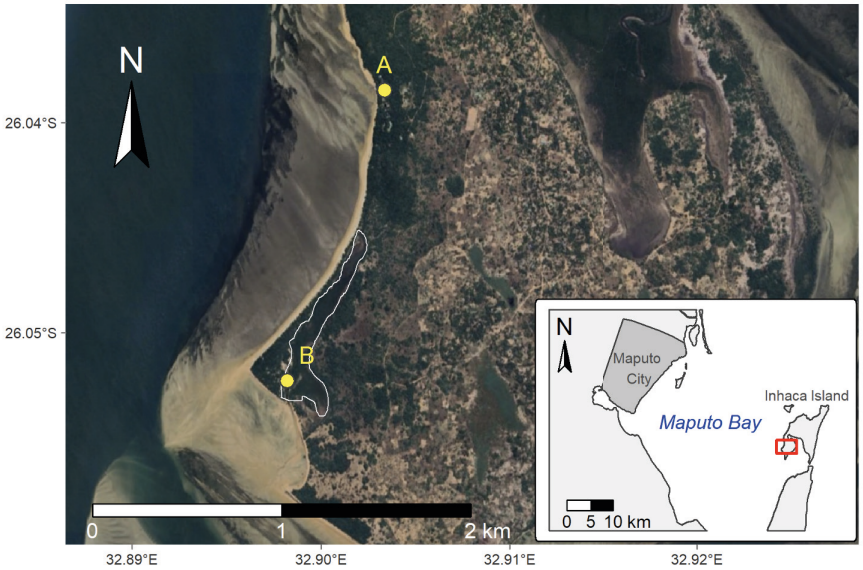

Figure 1. Study area and station points: (A) Inhaca Marine Biology Station (EBMI); (B) Ponta Raza. The boundaries of the Ponta Rasa mangroves are outlined by the white polygon. Base image from Google Earth©.

of the island's area (Barbosa, 1995) and is primarily composed of reed communities, notably *Phragmites australis*, with submerged flora being rare (Kalk, 1995).

Inhaca also supports mangroves, a critical component of its coastal ecosystem, primarily located along sheltered bays that receive some freshwater input, such as Sangala (northwestern), Saco (central), and Ponta Rasa (southwestern). These mangroves cover an area of approximately 308 ha (~ 7% of the island's area) and are dominated by species such as *Avicennia marina, Rhizophora mucronata*, and *Ceriops tagal* (Kalk, 1995). They play a vital role supporting biodiversity, and providing nursery habitats for marine species (de Boer, 2002; Guerreiro et al., 1996; Macia et al., 2001; Macnae & Kalk, 1962a).

Inhaca Island is uniquely positioned near the southern limit of the fauna and flora typical of East Africa's tropical coasts and the northern limit of the fauna and flora found along the coasts of Natal and Southeast Africa. Located at latitude 26º So, it hosts some of the southernmost

coral reefs and mangroves in the world (Kalk, 1995; Macnae & Kalk, 1962a)

At low tide, a vast stretch of beach is exposed, revealing seagrass meadows that serve as a food source for turtles and dugongs, occasionally spotted in the channels surrounding the island. These meadows also provide a rich hunting ground for mollusks, echinoderms, and crabs, which take shelter among the leaves and stems during low tide. According to Macnae & Kalk (1962b, 1962a), who conducted the first studies on the distribution of animals and plants across Inhaca's sandy and muddy plains exposed at low tide, a strip extending up to about 4 kilometers from the high-water mark to the low water level, approximately 400 species of animals can be recorded in this zone.

B. *Tides during installation and maintenance activities*

The tides are semidiurnal, with a spring tidal range of 2.2 m and a neap tidal range of 0.7 m. The tidal volume differences, based on water depth and the bay area of 15,400 ha, are estimated to be 26×10^6 m^3 during spring tides and 16×10^6 m^3 during neap tides (de Boer et al., 2000).

We consulted tide forecasts to determine the optimal time for installing the station in the mangrove (Figure 2). Managing the bioacoustics station during high tide would have presented significant challenges due to the mud and water, especially when handling sensitive electronic components and cables.

C. *Observing stations setup*

We conducted bioacoustics monitoring at two sites on Inhaca Island, from October 1st to 8th, 2024, with additional recording days thereafter. We selected the first station near the Inhaca Marine Biology Station (S 26.047, E 32.901) in a dune closed forest and the second at Ponta Rasa mangrove (S 26.052, E 32.898). We performed a preliminary survey to assess site suitability and identify precise equipment placement for optimal acoustic data collection.

At each station, we deployed a Zoom P4 Podtrack recorder (Figure 3) connected to one microphone and three hydrophones, positioned

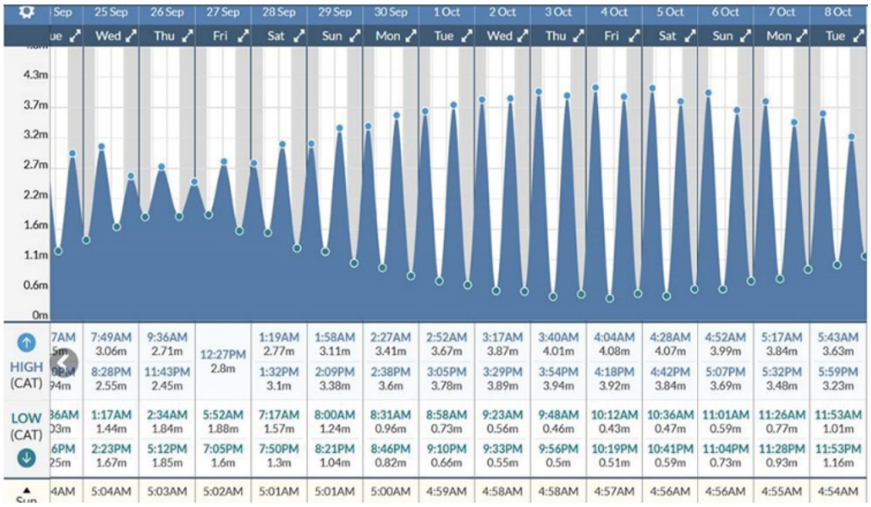

Figure 2. Tide variation during the station installation and data collection at Ponta Rasa mangroves (information from www.tide-forecast.com).

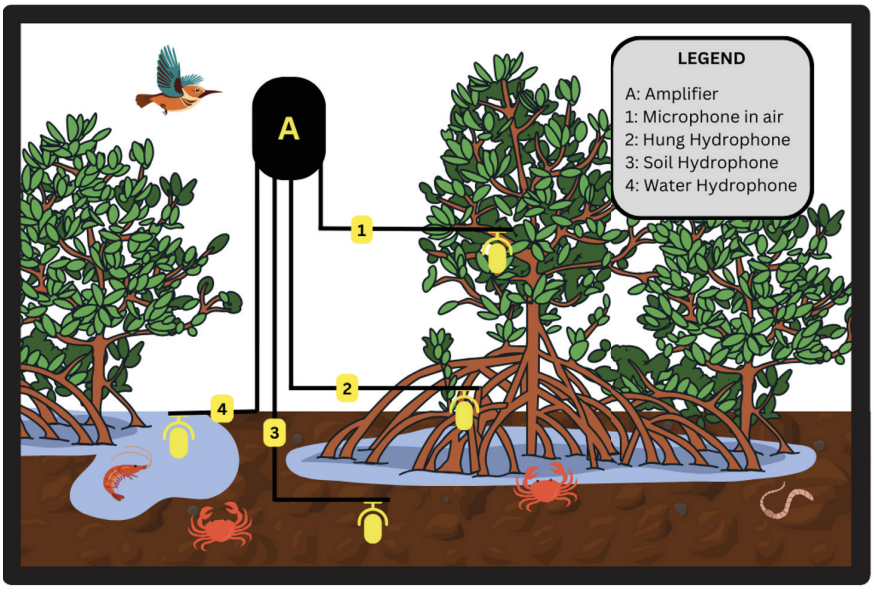

Figure 3. Setup of the bioacoustics station experiment at Ponta Rasa mangrove.

to capture a wide range of soundscapes (Figure 4). We elevated the microphone above ground level to record atmospheric sounds, securing it inside a bottle with cable ties and wooden sticks to prevent contact with the interior walls, which could introduce noise. We protected the microphone with a self-made shield against rain and wind, leaving the tip exposed for omnidirectional sound capture, to guarantee both, protection from external factors while retaining the microphone's ability to record sounds from any angle. We configured the three hydrophones as follows:

Suspended one ~ 5 cm above the soil from a mangrove root before high tide to ensure submersion during high tide and exposure during low tide.

Buried another ~ 50 cm deep in a hole created with a soil driller, partially covering it with mud to stabilize the device, reduce background noise, shield it from environmental elements, and enhance ground-based sound detection.

Kept the third continuously submerged in a nearby channel, ~ 10 m from the other devices, to record underwater sounds.

Our instrumentation weighed < 1 kg circa, depending on the power bank's capacity, with the core system (amplifier, data acquisition, and power supply) measuring < 20 × 20 × 20 cm.

We installed the equipment during low tide (e.g., predicted for 8:58 AM on October 1st, 2024, at Ponta Rasa, with setup at ~ 9:00 AM) to simplify access to shallow areas, enhance safety, ensure accurate positioning, and minimize sediment burial risks. We collected data near the Inhaca Marine Biology Station from October 1st to 3rd, 2024, and at Ponta Rasa from October 4th to 8th, 2024.

Our recordings were segmented into 3h22m53s intervals due to the data acquisition board's automatic stop at 0.99 GB, with brief gaps between files caused by data archiving to the SD card. We replaced power banks daily, which introduced anthropogenic noise (e.g., footsteps), affecting the first and last 15 minutes of each day's recordings. We also observed additional human activity near both stations during setup and data collection, contributing to background noise at the start and end of recordings.

Figure 4. Illustration of the four acoustic sensors installed at the Ponta Rasa bioacoustics station: (1) aerial microphone; (2) suspended hydrophone; (3) hydrophone suspended and positioned near the bottom left; (4) submerged hydrophone.

D. *Acoustic analysis*

We conducted preliminary analysis using Audacity® (version 3.6.4) and visually examined audio files through spectrograms, which are graphical representations of sound frequency spectra over time, displaying frequency (y-axis), time (x-axis), and amplitude (color intensity) (Flanagan, 1972). Spectrograms were created using Kaleidoscope Lite (version 5.6.6) to detect signals and identify their sources whenever feasible.

V. Results and discussion

All the acoustic sensors successfully detected different soundscapes (Appendix A). These soundscapes varied according to environmental cycles, such as time of the day (sunrise, sunset, daytime, nighttime) and tidal fluctuations (low tide and high tide).

Regarding the microphone in the air, we observed variations in spectral energy, particularly during sunrise, when bird activity increases. Similarly, the transition from day to night was marked by changes in both the energy levels and the types of sounds recorded, suggesting a shift in bird species, including nocturnal ones. Wind had a significant impact on the recordings at the first station, especially before the windscreen was improved. This interference was most prominent during the day and often saturated the recordings, masking other simultaneous acoustic signals.

Concerning the hydrophones, the suspended unit detected energy changes that followed tidal movements. Increases in spectral energy were recorded as the tide rose, likely due to the sensitivity of the hydrophone to the surrounding medium. Conversely, as the tide receded, a decrease in energy was observed, supporting our initial hypothesis.

The hydrophone placed under the soil produced data that were particularly challenging to interpret due to the limited number of studies on this application, especially in mangrove environments. Nevertheless, the instrument captured a variety of subterranean sounds in areas where the soil remained moist for extended periods. Decapod crustaceans, such as fiddler crabs (*Uca* spp.), with their varied morphological features, likely contributed to these auditory signals through behaviors

like claw snapping (Boon et al., 2009). Moreover, results were also influenced by specific human-generated noises and natural environmental factors (Rahim et al., 2024), despite the study site's minimal anthropogenic activity.

The final hydrophone, fully submerged in a tidal stream, recorded sounds influenced by water flow and by the presence of aquatic organisms typical of this habitat, such as fish, crabs, and shrimps.

A more detailed analysis was published elsewhere (Moretti et al., 2025; Nhancale et al., 2025).

A. *What we learned*

Despite our preliminary planning, we encountered various difficulties during fieldwork, particularly in positioning and installing the equipment. Most of these issues were identified and resolved during the installation of the first station, which allowed us to carry out subsequent installations more efficiently.

The primary limitation was environmental: mobility was hindered by mud, puddles, and unstable surfaces. These conditions complicated not only the installation process but also routine tasks such as replacing batteries and memory cards. Consequently, we required a team of at least three people for most operational activities. To ensure time efficiency and effectiveness, we found it essential to clearly assign and discuss responsibilities within the team beforehand. On average, reaching Station B (Ponta Rasa) took 20 minutes, while Station A (EBMI) required approximately 45 minutes. Installing a station took about one hour, whereas routine maintenance took significantly less time (approximately 5 minutes).

Additional challenges arose concerning power supply and instrument positioning. Although our goal was to maintain a low-cost setup, we recommend investing in reliable power banks or ensuring that the chosen equipment has a favorable price-to-performance ratio, allowing for multiple days of operation without requiring daily battery replacement.

We experienced the greatest difficulties in positioning the microphone in the air, primarily due to wind interference. We only became aware of the intensity of this disturbance after reviewing the first recordings, which revealed that the wind noise saturated the 16-bit dynamic range

of the amplifier. Based on this experience, we recommend fully covering the microphone with a windscreen to minimize acoustic disturbances. Moreover, during memory card replacements, the gain knobs for both the microphone and hydrophones can be unintentionally altered when removing the windscreen. We therefore advise checking the settings before and after any manipulation of the equipment.

The positioning of the suspended hydrophone also required careful consideration. Although our intention was to keep it submerged for most of the tidal cycle, at the first station we installed it on an elevated area of the substrate. As a result, the hydrophone was not continuously submerged, even during high tide. For the second station, we conducted a more thorough analysis of the terrain, which allowed us to place the hydrophone in a location where it remained submerged for a longer period. This was confirmed during maintenance on October 5, 2024 at 9:22 am, when we found the third hydrophone partially submerged. At that time, the tide was at 1.4 m, following a high tide of 3.5 m at 05:24 am and preceding a low tide of 0.4 m at 11:33 am (according to www.tide-forecast.com).

While our setup has great potential for acquiring long time series of data — comprising multiple ~1 GB files recorded at 16-bit and 44,100 Hz across four channels — managing such large volumes of digital storage and developing time-intensive acoustic pattern recognition models presents a challenge. One day of recording generated approximately 30 GB of data, which scales rapidly with multi-day deployments. To address this, we segmented the recordings and selected specific time intervals of interest (e.g., dawn, dusk, high tide, and low tide) for focused analysis. Further statistical analysis should be conducted to determine whether there are significant temporal differences between the two stations and across different times of day.

B. *Pros and cons of the used bioacoustics station*

Pros: The system is affordable, low-cost, and designed for ease of installation, use, and transport. It enables simultaneous monitoring of atmospheric, terrestrial, and aquatic environments, making it a versatile tool for multi-domain environmental studies.

Cons: Currently, the system's endurance is constrained by the power supply, necessitating daily maintenance. The large volume of generated data poses challenges in terms of data handling and storage capacity. Additionally, the limited dynamic range of the amplifier requires case-specific adjustment of gain settings, depending on the surrounding soundscape. The aerial microphone must be properly shielded to prevent signal saturation in high wind conditions. Accurate analysis of tidal cycles is also essential to ensure appropriate placement of hydrophones for effective aquatic monitoring.

Signal recognition and interpretation — particularly for hydrophones placed in soil and water — can be challenging due to the very limited or nonexistent availability of reference libraries for these environments.

C. *Future directions*

Based on the lessons learned, we suggest the following precautions and recommendations for future works:

- Once in the designated work area, the team should carefully study the surroundings to determine the optimal placement for the instruments. A preliminary site inspection may be useful to minimize setup time.
- Identify hidden or strategic locations for equipment installation to avoid human contact or interference, which could compromise the dataset.
- Raise awareness about the potential of using bioacoustics instruments to monitor mangrove ecosystems, emphasizing their affordability and ease of use.
- For future applications, we also recommend including additional instruments, such as an anemometer and camera traps, to better characterize the recording environment and contextualize the captured signals.

Our work aimed to demonstrate the feasibility of monitoring mangrove ecosystem soundscapes using relatively simple instrumentation. We hope this represents the first of many monitoring initiatives in Inhaca and across Mozambique. We also intend this paper to serve as a procedural guideline, enabling technicians to replicate the methodology, with adjustments based on site-specific conditions.

VI. Conclusion

The integration of bioacoustics equipment in mangrove ecosystems marks a pioneering yet underexplored approach to environmental monitoring. Employing a trial-and-error methodology with ongoing adjustments, this study developed accessible and adaptable protocols tailored to the diverse ecological conditions of mangroves, such as variable tidal patterns and sediment compositions. These efforts establish a foundation for standardized bioacoustics techniques, enabling broader application across complex coastal habitats.

This innovative setup produced a robust dataset, demonstrating the effectiveness of simple bioacoustics tools in capturing biological cues, such as decapod crustacean vocalizations, and environmental dynamics, including tidal fluctuations. The experiment's success highlights the potential for these systems to be deployed across various mangrove locations, offering scalable solutions for ecological monitoring. Moreover, these findings emphasize the pivotal role of bioacoustics in advancing mangrove conservation by providing critical insights into ecosystem health and biodiversity.

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Figure 5. Fiddler crabs (Decapoda: Brachyura: Ocypodidae), such as the Tubuca urvillei in the photo, form an essential part of the marine food web. Through bioturbation: their burrowing and foraging mix sediments and modify mangrove substrate properties, supporting ecosystem health. Most notably, fiddler crabs enrich the mangrove soundscape: males reduce unique sounds by rapping their enlarged claw against the ground or emitting honking calls, using these signals for nocturnal courtship, territorial defense, or competition with other males (photo by Paolo Ramoni-Perazzi).

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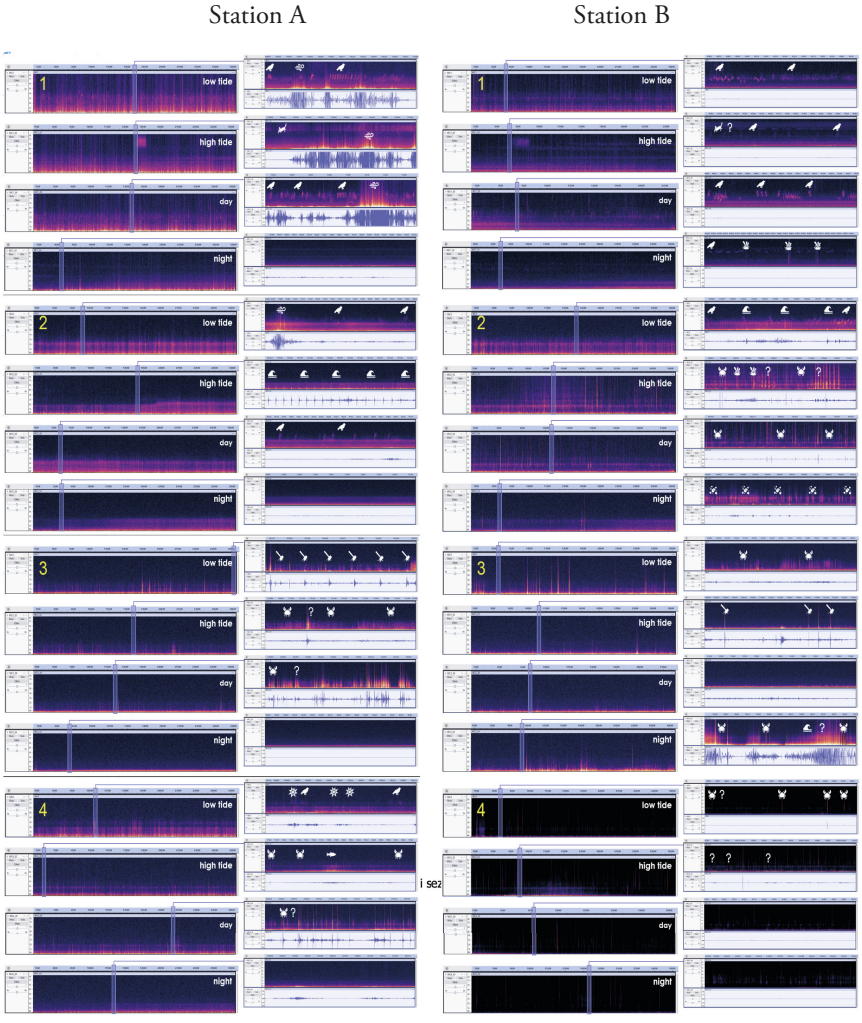
Appendix A. A sample of the soundscapes recorded using different devices at Stations A (EBMI, group on the left) and B (Ponta Rasa, group on the right). Each group shows a broad time sample taken at different moments (low or high tide, day or night) on the left, and a detailed view on the right. Icons suggest specific sound sources: birds, wind, waves, human activities, crabs, fish, and unknown sources.



THE SOCIOECONOMICS OF THE ARTISANAL FISHERY SECTOR
THE SPECIAL CASE OF THE INHACA ISLAND

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Abstract: Artisanal fishing and crustacean collection are critical livelihood activities in coastal Mozambique, yet their dynamics and sustainability remain underexplored. We investigated these practices on Inhaca Island, southern Mozambique, to assess their socio-economic contributions and conservation perspectives. We interviewed 34 artisanal fishers and shellfish collectors using structured questionnaires, capturing demographic data, capturing practices, and perceptions of mangrove ecosystems. Interviews with fishers occurred at the *Conselho Comunitário de Pesca*, while female collectors were engaged in beach activities. Our findings indicate that adult men supporting households of over four members primarily fish, harvesting 11.0 kg daily, which is sold at 192.5 MZN per kg. Young women, supporting up to six household members, collect crustaceans, averaging 3.0 kg daily, mainly for household consumption, with occasional local sales at 87.5 MZN per kg. Both groups reported declining

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catches and emphasized the importance of mangrove conservation for the community's benefits. We conclude that fishing and crustacean collection are vital for Inhaca Island's livelihoods, providing essential income and protein, underscoring the need for mangrove ecosystem preservation to ensure sustainability.

Keywords: Crustaceans, Artisanal fishing, Mangrove, Inhaca Island.

I. Introduction

Mangrove ecosystems are salt-tolerant evergreen forests found in intertidal zones at the interface of land and sea. They occur in tropical and subtropical regions worldwide, along coasts, shallow lagoons, estuaries, rivers, and deltas, primarily on soft substrates (FAO, 2023; Rivera-Monroy et al., 2017). These ecosystems are characterized by a small group of species with specialized adaptations for surviving saline and intertidal conditions (Naidoo, 2023).

In Mozambique, mangroves span over 300,000 ha along the coastline, the second largest area in Africa after Nigeria (Fatoyinbo & and Simard, 2013). These ecosystems provide critical goods and services, including coastal protection, carbon sequestration, habitat for marine species, and a source of income and economic support for local communities (Kairo et al., 2020; Macamo et al., 2021; Montaggioni, 2011). Extreme poverty and limited alternative income sources make mangroves vital for supplying goods such as fuelwood, fish, crustaceans, medicines, and materials for constructing boats and homes in Mozambique's coastal regions (FAO, 2023; Macamo et al., 2021; Macamo & Sitoe, 2017). Fish, mollusks, and crustaceans are key fishing resources supporting human populations in these coastal ecosystems (Gomes, 2015; Severino-Rodrigues et al., 2002). Consequently, they represent a primary form of mangrove resource use by coastal communities (Njagi et al., 2013). On Inhaca Island specifically, fishing and crustacean collection is the main income source for 20% of the population (Costa et al., 2020; Hoguane, 2007; Manuessa et al., 2024; Mugabe et al., 2021)., with 27% of animal protein intake derived from fish, crustaceans, and other marine resources (World Bank Group, 2018).

Despite the socioeconomic importance of fishery resources for coastal communities in Mozambique, assessing them is complex and requires analyzing regional dynamics and community customs (Massamba, 2016). Studies on the dynamics of artisanal fishing on Inhaca Island remain scarce despite its critical role in the local economy.

Understanding the dynamics of artisanal fishing on Inhaca Island can support effective public policies to provide essential services and promote self-sufficiency in fishing communities (Francisco et al., 2021; Mugabe et al., 2021).

This study aims to: i) describe the socio-demographic structure of groups engaged in artisanal fishing and crustacean collection on Inhaca Island; ii) analyze the dynamics of these activities among fishers and crustacean collectors; and iii) evaluate their perceptions of the need for mangrove protection and restoration.

II. Material and methods

A. *Characterization of the study area*

We conducted the study in the Ribjene and Nyakeni communities on Inhaca Island, located 32 km east of Maputo City (Figure 1), between 25°57'S to 26°05'S and 32°53'E to 33°00'E. The island, spanning approximately 42 km², is the largest of the two islands forming the Inhaca Archipelago (Pereira & Nascimento, 2016). The region experiences a humid tropical climate, with a mean annual temperature of 22–23°C, mean annual rainfall of 600 mm, and annual relative humidity of 76% (Muacanhia, 2003).

The vegetation of Inhaca comprises both terrestrial and aquatic-marine species, varying according to the soil and climate conditions of the mainland. On this island, coastal forests dominate the dunes of the eastern coast; forests feature scattered trees separated by extensive areas of grasses, associated or not with small shrubs; floodplain vegetation exhibits a distinct composition, consisting primarily of reed

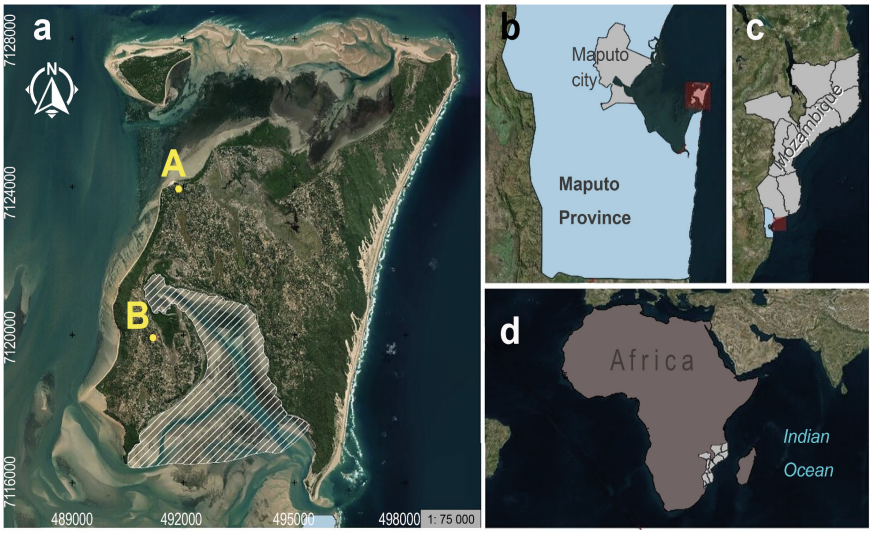

Figure 1. Geographic location of the study area. (a) Google Earth image of the Inhaca Archipelago, showing the locations of the Ribjene (A) and Nyakeni (B) communities, as well as Saco, the shellfish harvesting area (dashed lines). (b) Location of the Inhaca Archipelago within Maputo Province and in relation to Maputo City. (c) Location of the archipelago within Mozambique. (d) Location of the archipelago in the context of Africa. Projection: Universal Transverse Mercator (UTM) Zone 36S. Datum: WGS 1984. Data source: CENACARTA.

communities (Phragmites australis) and rarely including submerged flora; and pioneer vegetation forms a carpet of succulent herbaceous species, occurring immediately above the high tide line on loose sand particles, where soils contain low organic matter, remain dry, show high salinity, and face strong ocean winds (Muacanhia, 2003).

Inhaca's economy depends on family farming, forestry, artisanal fishing, small-scale livestock farming, trade, and tourism. Farmers cultivate main crops such as corn, cassava, sweet potatoes, peanuts, beans, watermelon, pumpkins, and sugarcane. Growers also raise fruit trees, including mango, papaya, coconut, citrus, and cashew, and their products supplement diets and incomes (Pereira & Nascimento, 2016).

Residents exploit natural resources to meet domestic needs without official control, and authorities permit cutting down trees for this purpose. However, to prevent dune expansion and the consequent loss of forests and agricultural land, regulations prohibit forest

Figure 2. Scenes from the data collection process on Inhaca Island Upper row: Interviews with fishermen at the Conselho Comunitário de Pesca (CCP) in Ribjene. Lower row: Crustacean collectors during their work in the Saco mangroves near the Nyakeni community (photos by Enrico Nicosia).

clearing for agricultural purposes. According to Zorini et al. (2004), harvesters infrequently collect large quantities of natural products, as limited transport restricts demand. Nevertheless, fishers and gatherers market fish and crabs, exchanging these goods for other products brought by visitors from the mainland who stopover on the island (Zorini et al., 2004).

B. *Sampling and data collection*

We conducted the sampling process intentionally, interviewing 34 volunteers after informing them of the study's purpose(2). Generally, we interviewed fishermen at the Conselho Comunitário de Pesca (CCP) in Ribjene and crustacean collectors during their work in the Saco mangroves near the Nyakeni community (Figure 2).

(2) Before starting fieldwork on the island, we obtained a permit from the local authority to conduct interviews, as the interviewees were illiterate and unable to sign consent forms.

We interviewed selected fishermen and crustacean collectors using a questionnaire comprising three main sections. The first section contained questions to gather socio-demographic information about each participant's household. We categorized interviewees into three age groups: young (15–35), adults (36–64), and elderly (over 64), following the National Statistics Institute (Instituto Nacional de Estatística - Moçambique, 2023). The second section included questions to collect data on the household's primary economic activities, fishing techniques, and dynamics. The third section focused on gathering information about the need to conserve mangrove ecosystems.

III. Data analysis

We categorized the demographic structure of groups commonly engaged in fishing and crustacean collection by gender and age group. Based on participants' descriptions, we determined fishing activity dynamics by assessing the frequency of activities, defined as the number of fishing or crustacean collection days per week. We gathered daily fish quantities from fishermen's statements and measured crustacean quantities by directly weighing buckets containing crabs.

Using weekly working time (hours and days) and the unit price of the harvested product, we calculated the catch to estimate the daily income for fishermen and crustacean collectors. We computed weekly revenue by multiplying daily revenue by working days and derived monthly revenue by multiplying weekly revenue by four weeks. Given the small sample size and significant data variability, causing a large discrepancy between the mean and standard deviation, we applied the median for calculations to ensure robust analysis.

We evaluated interviewees' perceptions of fishing dynamics by analyzing response frequencies in the categories "fishing increased," "no changes," and "fishing decreased" over the past five years. Additionally, we assessed their perceptions of mangrove ecosystem conservation needs using the categories "importance for family livelihood," "recreation," "protection against extreme events," "protection of biodiversity," and "benefits for future generations".

IV. Results

A. *Demographic aspects*

We identified and interviewed 34 individuals, of whom 18 (53%) were men (fishermen and members of the *Conselho Comunitário de Pescas*-CCP) and 16 (47%) were women who collect crustaceans within the island's mangrove ecosystem.

The majority of the individuals we interviewed were young people (47%) and adults (50%). Young people constituted the largest group of crustacean gatherers, whereas adults comprised the majority of fishermen engaged in artisanal finfishing on the high seas. Generally, both fishermen and crustacean collectors reside in households with up to four individuals per household (Table I).

B. *Socio-economic dynamics*

We observed that the frequency of finfishing and shellfishing depends on several factors, including tidal intensity and wind direction. Low tides facilitate crustacean gathering, whereas high tides and north-south winds promote finfishing on the high seas. According to the individuals we interviewed, we noted that they engage in finfishing or shellfishing daily whenever conditions are favorable. Specifically, among the Inhaca fishermen, we recorded fishing activity occurring 4 to 6 days per week, while crustacean gatherers work up to 3 days per week (Figure 3).

Our results indicate that the production from deep-sea finfishing, conducted over 5.0 hours, yields approximately 11.0 kg/day of effective labor, primarily intended for sale in the local market for 192.5 MZN/kg (Table II). Conversely, we found that the daily collection of crustaceans, conducted over 2.0 hours, yields approximately 3.0 kg/day. We observed that this production is generally allocated for household consumption, with sales occurring only in exceptional cases when commissioned by third parties, for 87.5 MZN/kg.

Based on the fishermen's statements, our findings indicate that the majority of their revenue ranges from 1,000.00 to 2,500.00 MZN per day (Figure 4). Fishermen's revenue averages 2,117.50 MZN/day and

Table 1. Demographic and socioeconomic profile of the fishermen and crustacean collectors, surveyed at Inhaca.

Activity		Finfihing	Shellfishing	Total
Gender	**Male**	18	-	18
		53%	0%	53%
	Female	-	16	16
		-	47%	47%
Age groups	**Young**	4	12	16
		12%	35%	47%
	Adult	13	4	17
		38%	12%	50%
	Old	1	-	1
		3%	0%	3%
Household members	**1 to 3**	4	7	11
		12%	21%	32%
	4 to 6	7	7	14
		21%	21%	41%
	7	7	2	9
		21%	6%	26%

53,900.00 MZN/month, whereas crustacean collectors' revenue averages 262.50 MZN/day and 2,100.00 MZN/month. These revenues represent gross income, as production costs are not included in the calculations.

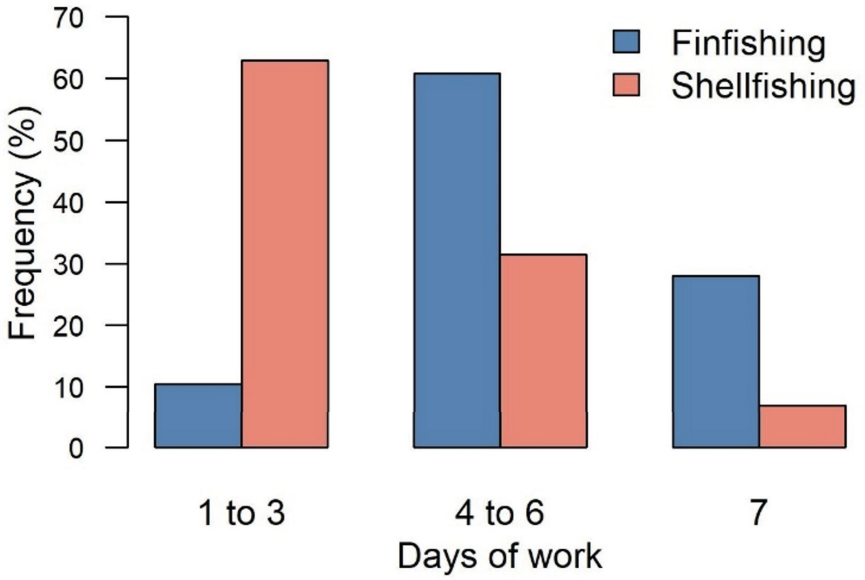

Figure 3. Weekly work frequency (%) among individuals surveyed on Inhaca Island.

Table 2. Statistical comparison of finfishing and shellfishing activities in the Inhaca Island, summarizing key metrics for daily catch, price, work hours, working days per month, and distance traveled by fishermen and crustacean gatherers.

Activity	**Finfishing**			**Shellfishing**		
	Median	Mean	Standard deviation	Median	Mean	Standard deviation
Daily catch (kg)	11.0	16.1	8.0	3.0	2.9	1.1
Price (MZN/kg)	192.5	172.8	34.3	87.5	87.5	17.7
Time of work (hours/day)	5.0	5.2	2.1	2.0	1.7	0.7
Working days per month	6.0	5.6	1.3	2.0	3.3	2.1
Distance (km)	5.0	6.3	3.6	2.0	1.7	0.5

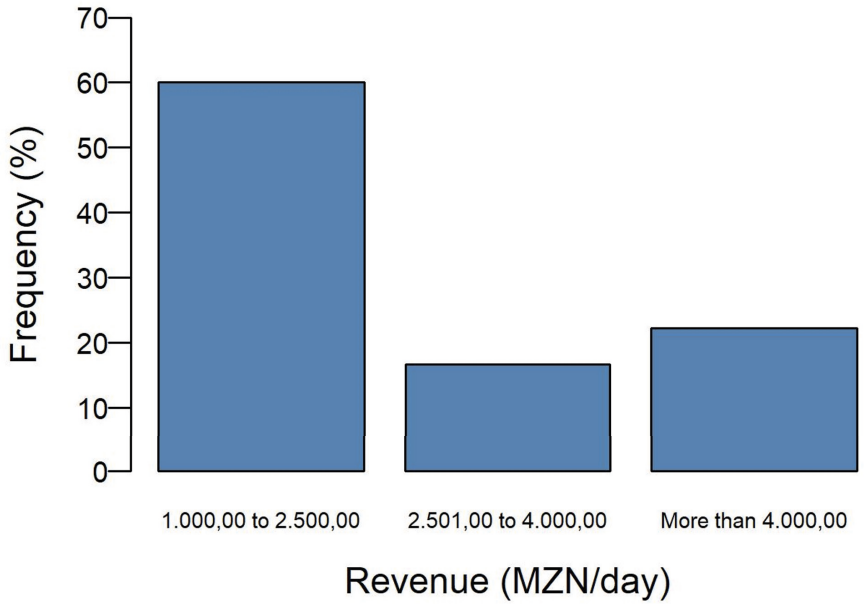

Figure 4. Distribution of daily revenue (MZN/day) among Inhaca fishermen and crustacean collectors.

Our interviews also reveal that most participants perceive a reduction in the daily quantity of fish and crustaceans compared to levels obtained over five years ago (Figure 3). The primary cause of this decline, according to respondents, stems from daily crustacean collection by the community and fishermen's use of nets with small mesh diameters (1 to 1.5 cm). A minor fraction (less than 15%) report, according to respondents, no difference between current and past catches, while fewer than 20% note an increased crustacean yield compared to five years ago.

The Figure 5 shows the perception of local communities about the importance of protecting or restoring the mangroves on Inhaca Island. For them, the mangrove is extremely important for their lives as it protects biodiversity, helps protect themselves from strong winds and other extreme weather events, constitutes a source of subsistence, and its conservation will allow future generations to enjoy these ecosystem services provided by the mangrove. In general, communities believe that mangroves are essential to their lives, as they depend on them to collect

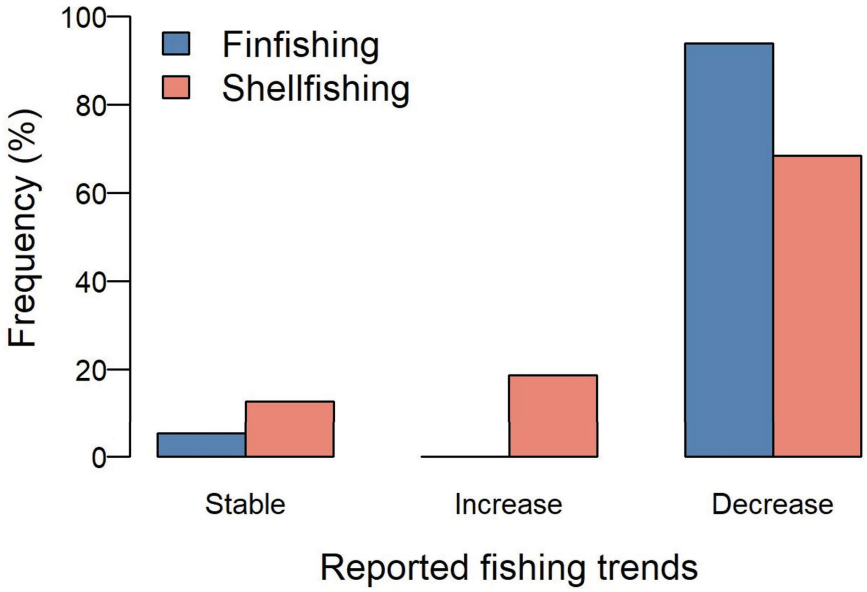

Figure 4. Perceived trends in the yield of finfishing and shellfishing activities, In the Inhaca Island.

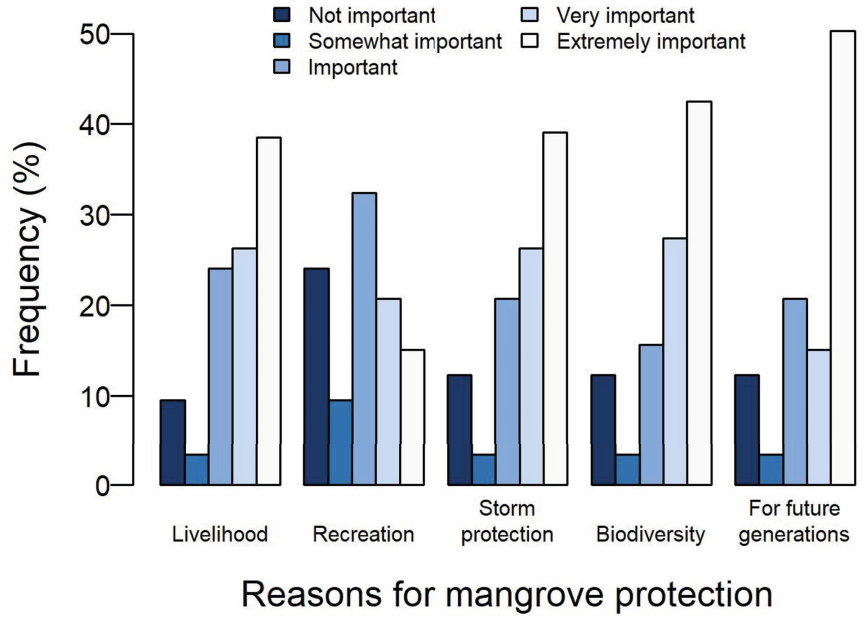

Figure 5. Perceived importance of various reasons for mangrove protection or restoration among Inhaca communities.

crabs for food. In contrast, communities consider mangroves to be of little importance for recreation and tourism activities.

V. Discussion

A. *Demographic aspects*

Based on our analysis, artisanal fishing in Mozambique serves as an income-generating activity, shaped by intricate logic tied to cultural beliefs, among others. Within these beliefs, men emerge as providers of the family economy, while women undertake domestic roles; hence, finfishing on the high seas predominantly involves men due to its economic returns (Arnfred, 2015; Tvedten, 2010).

Our findings indicate that the demographic profile of fishermen and crustacean collectors aligns with Mozambique's economically active age range, spanning 15 to 65 years (Hoguane, 2007), and mirrors the demographic composition of Kanyaca district, a Maputo community where youth predominantly dominate the age distribution (INE, 2022). High unemployment rates among this age group in the country drive younger individuals to pursue activities like fishing to fulfill economic needs (INE, 2023). The demographic profile of fishermen also reflects trends observed in estuarine fisheries across several countries, including Tanzania (Katikiro, 2014) and Kenya (Karama et al., 2016), where an older age distribution prevails, linked to techniques such as beach fencing, a form of gillnetting requiring significant physical effort and strength for effective operation.

B. *Socio-economic dynamics*

Based on our analysis, artisanal fishing and crustacean collection contribute to job creation, providing nutrition and sustenance for numerous families across Africa (Eshun et al., 2019). In Maputo Bay (comprising Inhaca Island), these fisheries play a vital role in local diets, with fish serving as a primary protein source for communities (Coetzee et al., 2015).

Findings reveal that the number of weekly fishing days depends on tidal conditions. High neap tides and favorable north-south winds enhance fishing success, attracting larger predatory fish that follow nutrient-rich currents and prey movements, thus increasing the likelihood of capturing commercially valuable species (Cavariato & Mualeque, 2013; Juliasse, 2018). Low spring tides facilitate crustacean collection, enabling gatherers to access sand and mud banks (Klaoudatos & Kapiris, 2014). Local knowledge, honed over generations, empowers fishermen and crustacean collectors to decipher fish behavior and optimal catching conditions, optimizing effort and efficiency by scheduling outings during peak success periods. Similarly, crustacean collectors adapt their activities based on tidal patterns, species availability, and experiential insights into ideal collection times (da Silva Mourão et al., 2020; de Sousa et al., 2022).

Survey responses indicate that fishermen sell their catch at approximately 192.5 MZN/kg. A substantial proportion (61%) report daily incomes between 1,000 and 2,500 MZN/day, while 17% earn 2,501 to 4,000 MZN/day, and only 22% exceed 4,000 MZN/day. This variation stems from factors such as fishing effort and declining fishery resources, worsened by climate change and a growing fisherman population (Eshun et al., 2019). Fishermen achieving higher earnings typically deploy more nets and workers; however, all surveyed individuals acknowledge a historical abundance of resources that has significantly diminished over time (Nhantumbo, 2019).

Regarding crustacean collectors, a survey by Mafambissa et al. (2024) reveals that 72.1% observe a decline in crustacean and bivalve populations due to overharvesting, potentially linked to collection methods and excessive daily collection. Most fishermen allocate part of their catch for home consumption and part for sale, whereas crustacean collectors utilize crabs solely for consumption Purcell et al., (2021). The lower selling price of crabs compared to fish reflects fishing's direct contribution to household food security over crustacean collection (Mehdi et al., 2021). Consequently, fishermen pursue daily fishing to boost monthly income.

C. *Importance of the mangrove*

Based on our interviews, the findings indicate that most participants recognize the relevance and urgency of conserving and restoring mangrove ecosystems, reflecting community awareness on Inhaca Island due to the significant contribution mangroves make to family income. This resonates with the findings of Maina et al. (2021), who previously illuminated that mangroves serve as a vital livelihood source for coastal communities, supplying food, building materials, firewood, and critical coastal protection against flooding, erosion, winds, and storms.

In Mozambique, we observe the harvesting of various fish, shellfish, and crabs from mangrove systems for sale and domestic use, corroborating earlier reports (Alati et al., 2020; Bandeira et al., 2009; Macamo & Sitoe, 2017). For example, the blue crabs (Portunus pelagicus) inhabit sandy and muddy bottoms in shallow waters at depths of 10 to 50 m, including areas near reefs, mangroves, seagrass, and algal beds (Rabaoui et al., 2021; Rizal et al., 2024). Though not mangrove-specific, they benefit from mangroves, particularly as nursery grounds for juveniles (Maryani et al., 2023). Mangrove biodiversity offers shelter, food, and protection, supporting early life stages (Kathiresan & Bingham, 2001; Longonje, 2014). While utilizing mangroves during certain life stages or tidal cycles, they rely on a broader ecosystem encompassing both mangrove and non-mangrove habitats (Glazner et al., 2020).

Results highlight a general positive awareness among fishermen and crustacean collectors regarding the mangrove ecosystem's importance for daily life and future generations. However, the perception of declining ecosystem-derived products over time underscores the need for restoration projects to sustain ecosystem function. Note that this study involved a small sample of 34 participants, and a larger sample would enhance understanding of the situation.

VI. Conclusion

Our study indicates that participants engaged in artisanal finfishing are men and adults supporting households exceeding four individuals,

while those involved in crustacean collection are women and youth-sustaining households of one to four people.

Findings reflect that, according to the majority of artisanal fishermen and crustacean collectors, the quantity of fish caught has declined over the past five years. Fishermen's revenue averages 2,117.50 MZN/day and 53,900.00 MZN/month, whereas crustacean collectors' revenue averages 262.50 MZN/day and 2,100.00 MZN/month.

For local communities, mangroves hold immense importance, safeguarding biodiversity and serving as a subsistence resource, with dependence on them for shellfish collection as a food source. Conversely, communities attribute minimal value to mangroves for recreation and tourism activities.

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Balancing the weight of her daily harvest, a woman at Noge (Inhaca Island) makes her way across the dense carpet of Avicennia pneumatophores. In front of her, a tangle of different mangrove species forms the backdrop, silent witnesses to her effort which sustains her family though it brings little economic return (photo by Paolo Ramoni-Perazzi).

INSIGHT INTO CARBON STOCK, BIOMASS AND FOREST STRUCTURAL DYNAMICS

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Abstract: Mangroves are coastal ecosystems that thrive in intertidal zones, encompassing ~0.4% of the global terrestrial forest area. Their complex aerial root systems support diverse fauna, stabilize soils, sequester carbon, and protect coastlines. We conducted this study in Saco Bay, Inhaca Island, to evaluate mangrove structure, diversity, and carbon stock, aiming to provide critical data for evidence-based conservation strategies ensuring long-term ecosystem sustainability. We established 10 circular (12 m ray) plots in contrasting mangrove stands for data collection (upper, middle, and lower areas within the forest). We collected soil samples within each plot, using a 100-cm-long auger (volume 353.25 cm^3) to extract samples of different depth intervals and estimate the amount of carbon stored. Within each plot, we identified, counted, and measured trees (height, DBH, canopy volume). We quantified downed wood debris by measuring volume and diameter using an aluminum gauge. To assess stand structure and calculate aboveground biomass, we used vegetation data, subsequently converted into aboveground and belowground carbon stocks. Through phytosociological parameters (frequency, density, dominance, importance value index), regeneration index, and tree trunk condition and quality, we were able to analyze forest structure. Results indicate a highly heterogeneous area in structure and carbon stock. Our findings underscore the critical role of Saco Bay's mangrove forests in carbon storage, emphasizing the necessity of conserving and managing these ecosystems, particularly in areas conducive to biomass accumulation and carbon sequestration.

Keywords: Mangrove conservation, Carbon storage, Inhaca Island, Conservation area.

I. Introduction

Mangroves are coastal ecosystems growing in the intertidal zones of tropical and subtropical climates, where freshwater and saltwater converge (Friess et al., 2019). Globally, there is growing recognition of the ecological, social, and structural importance of these forests (Hagger et al., 2022). Spanning roughly 152,000 km^2 (Spalding et al., 2010), these forests may represent just 0.4% of the global terrestrial forest area, but their ecological significance far outweighs their limited size. Their complex aerial root systems provide habitat for diverse species while stabilizing soils, sequestering and storing carbon, and protecting coastlines (Abou Seedo et al., 2017; Adame et al., 2021; Lagomasino et al., 2019; Njana et al., 2016; Zhang et al., 2016).

Mangroves are exceptional carbon sinks, efficiently storing large amounts of carbon in their biomass and soils (Kauffman et al., 2020). Due to their high primary productivity, these ecosystems often form dense forests with complex aerial root systems that act as natural filters, capturing both autochthonous and allochthonous materials, including carbon. The soils, however, serve as the main reservoir for carbon stocks, as the waterlogged and low-oxygen conditions slow decomposition, allowing carbon to accumulate over time. On average, the total ecosystem carbon stock in mangroves globally is 856 ± 32 Mg C/ha, with an estimated global carbon storage of 11.7 Pg C—1.6 Pg C in aboveground biomass and 10.2 Pg C in belowground carbon (Kauffman et al., 2020). This is equivalent to 1.15 times the global annual CO_2 emissions (37.25 x 10^9 Mg CO_2 in 2021 (Ritchie & Roser, 2020). Preserving these ecosystems is essential, as their degradation could release vast amounts of carbon into the atmosphere, fueling greenhouse gas emissions and intensifying climate change.

Despite these numerous ecological services, approximately 50% of the world's mangrove forests have disappeared over the past 50 years (Alongi, 2014; Donato et al., 2011). The main drivers of these losses are anthropogenic, including land conversion for agriculture and aquaculture, timber harvesting, coastal development, and marine pollution from oil exploration (Wang et al., 2021). Natural drivers, such as extreme weather events and shoreline erosion, are also significant

contributors to mangrove loss, and their impact is intensifying due to climate change, further accelerating the rate of mangrove degradation (Goldberg et al., 2020).

In Mozambique, the decline of mangrove forests is driven by both persistent and emerging threats, including salt production, excessive logging, urban expansion, reduced freshwater flow from damming, and pollution (Amade et al., 2019; Barbosa et al., 2001). More recently, rapid population growth, urbanization, and climate-related migration have added pressure to coastal regions (Cianciullo et al., 2023; Serra, 2012). Between 1996 and 2020, Mozambique lost 159.1 km^2 of mangroves (Global Mangrove Watch, 2024), with ongoing threats such as erosion (45.19%), wood harvesting (27.67%), climatic events (25.41%), and settlements (1.44%) continuing to impact these areas (Goldberg et al., 2020). Despite 53.72% of mangrove areas being protected, 17,932 disturbance alerts were recorded from 2019 to 2024, and 90 hectares were lost annually (Conselho de Ministros, 2020). With rising temperatures and sea levels, climate change will further exacerbate these pressures and alter mangrove ecosystems.

In addition, the lack of a comprehensive understanding of mangrove structure and diversity hinders the development of effective conservation policies (Akram et al., 2023). To address this gap, our study aims to evaluate the structure, diversity, and carbon stock of mangroves, providing crucial data to guide the creation of evidence-based conservation strategies that ensure the long-term sustainability of this vital ecosystem. Monitoring mangrove biomass and structural attributes is essential to track changes and implement adaptive management, which is crucial for protecting these ecosystems from the increasing pressures of human activity and climate change. To ensure consistency and comparability with global mangrove assessments, we apply a protocol and sampling design that comply with international standards outlined in the guidelines of the Intergovernmental Panel on Climate Change (Eggleston et al., 2006). This standardization facilitates accurate, comparable measurements of mangrove carbon stocks and biomass worldwide, contributing to global mangrove conservation and climate change mitigation efforts.

II. Objectives

A. *General*

To evaluate the structure, diversity, and carbon stock of mangroves in order to provide evidence-based data for developing effective conservation strategies that ensure the long-term sustainability of these ecosystems, while adhering to standardized international protocols for global comparability.

B. *Specific*

- Estimate the biomass of different mangrove species in Saco da Inhaca.
- Describe the forest structure and spatial distribution of the main mangrove species in Saco da Inhaca.
- Estimate the system's carbon stock.
- Compare the structure and biomass of the mangrove stands with different tidal exposures in the Saco da Inhaca.

III. Materials and methods

A. *Study area*

Inhaca Island lies in the Indian Ocean, approximately 32 km east of Maputo, the capital of Mozambique (26°S latitude, 33°E longitude; Figure 1). Spanning 40 km², the island extends 12.5 km from its northernmost point (Ponta Mazondue) to its southernmost point (Ponta Torres). The research area encompasses an interior mangrove forest of approximately 15.4 km², located at the end of an 8 km channel in Saco Bay, at the southern tip of the Island.

The ecological resources of the mangrove ecosystem are fundamentally important for Inhaca's population of 6,000 inhabitants, most of whom reside in coastal villages (Bandeira & Paula, 2014). These ecosystems provide critical resources for local communities, including

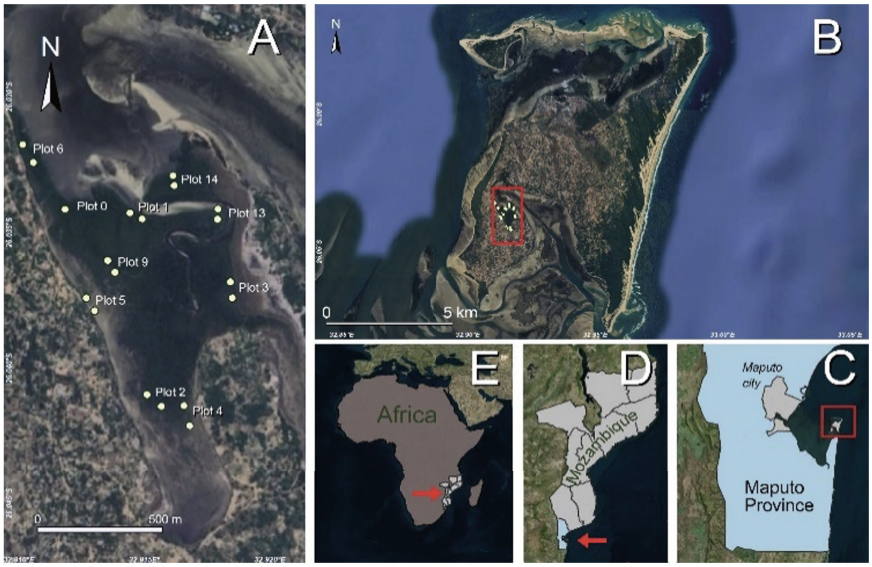

Figure 1. Geographic location of the study area. (A) Distribution of sampling stations within the Saco mangrove. (B) Location of the sampling stations in the context of Inhaca Island. (C) Location of Inhaca Island within Maputo Bay (red box). (D) Position of Maputo Bay within Mozambique. (E) Location of Mozambique in Africa.

fuelwood, construction materials, medicinal plants, and sustenance from mangrove fisheries, timber, and tannins (Ramoni-Perazzi & Attorre, 2024).

The region's climate is humid subtropical (Köppen-Geiger: Aw), with two distinct seasons: summer and winter. Summer, spanning October to April, exhibits higher rainfall and temperatures (100–151 mm per month, 25–28°C), whereas winter experiences lower rainfall and cooler temperatures (12–29 mm per month, 21–25°C). The annual average rainfall measures 800 mm, peaking in January (77 mm) and reaching its lowest in May (2.5 mm). The tidal cycle at Inhaca follows a semi-diurnal pattern, with water temperatures ranging from 17°C to 37°C (Macnae & Kalk, 1962).

The Saco mangrove forest, triangular in shape, is traversed by a main natural channel that narrows and fades at higher inland elevations. Saco ranks among the densest and most pristine mangrove areas on Inhaca Island, colonized by five mangrove species: *Avicennia marina*,

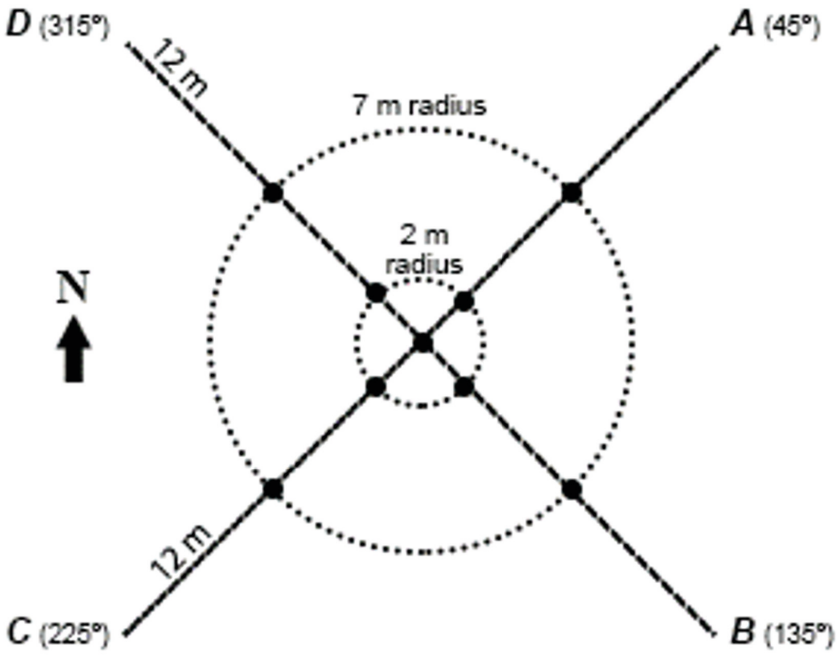

Figure 2. Subplot layout design divided into four quadrants by wood debris transects oriented at 45°, 135°, 225°, and 315° from North. Transects extend 12 m from the center. Dashed circles indicate sampling zones with 2 m and 7 m radii for trees ≤5 cm and >5 cm DBH, respectively. Points indicate the flagging tape marks. North is indicated for reference. Adapted from (Kauffman & Donato, 2012).

Rhizophora mucronata, *Ceriops tagal*, *Bruguiera gymnorrhiza*, and *Lumnitzera racemosa* (de Boer & Longamane, 1996).

The combination of these species forms a complex, highly productive ecosystem that is essential for local biodiversity, coastal protection, and carbon sequestration. Furthermore, it serves as a vital source of food and income for local communities who fish with nets and harvest crabs in the inner waters of Saco Bay.

B. *Sampling design and data collection*

We collected data within 10 plots established in contrasting mangrove stands to maximize exploration of the study area. In each plot, we established two circular subplots with a 12 m radius (0.045 ha) and

positioned them 25 m apart. To define each subplot, we located the center using GPS, and demarcated two 24 m lines at a 45° angle from North (one to the left and one to the right) using a compass and two perpendicular measuring tapes, forming four quadrants in each subplot (Figure 2).

C. *Soil and Salinity*

We selected a smooth, undisturbed area of soil within each subplot, and sufficiently distant from tree trunks to facilitate drilling, for the soil and salinity sampling procedure.

For soil extraction, we inserted a 100 cm long auger (volume of 353.25 cm^3) into the chosen spot, twisted it, and removed it to obtain the soil sample (Figure 3A). After extraction, we placed the auger horizontally and measured the core length with a tape measure (Figure 3B). Using a bread knife, we cut the core transversely to form a perfect half-cylinder shape for precise volume calculation. We determined the volume by multiplying the length of the sampled depth interval by the area of the half-cylinder. In some cases, the gradient of soil composition along the core was visible (Figure 4A), providing additional insight into sample stratification.

We collected interstitial pore water from the soil core sampling spot using a pipette (Figure 3D) to measure salinity (‰) with a refractometer (Figures 3E, F). We repeated the salinity measurements three times and recorded all values in a spreadsheet alongside the soil data and other qualitative information about the sampling point.

We collected soil samples at depths of 0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, and 50–100 cm along the soil core (Figure 3B). When the entire depth interval was not collected, we recorded the precise depth of the sampled interval to calculate the exact volume for bulk density, carbon (C), and organic matter (OM) analyses. We placed each sample in a separate Ziploc bag (Figure 3C), sealed it after removing most of the air to prevent oxidation, and stored the samples in a refrigerator at -15°C until laboratory analysis, whose results will be published elsewhere.

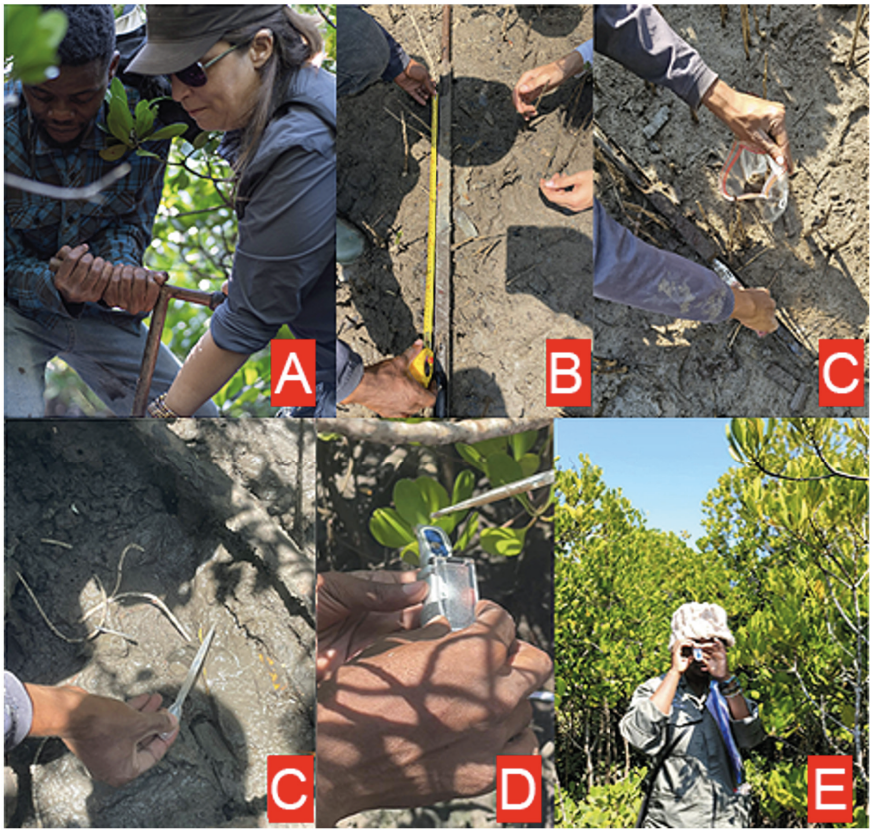

Figure 3. Sampling moments during fieldwork at the mangroves of Saco da Inhaca. (A) Soil extraction; (B) measurement of soil core length; (C) collection of soil core sections in plastic bags; (D) water sampling using a pipette; (E, F) salinity analysis with a salinometer.

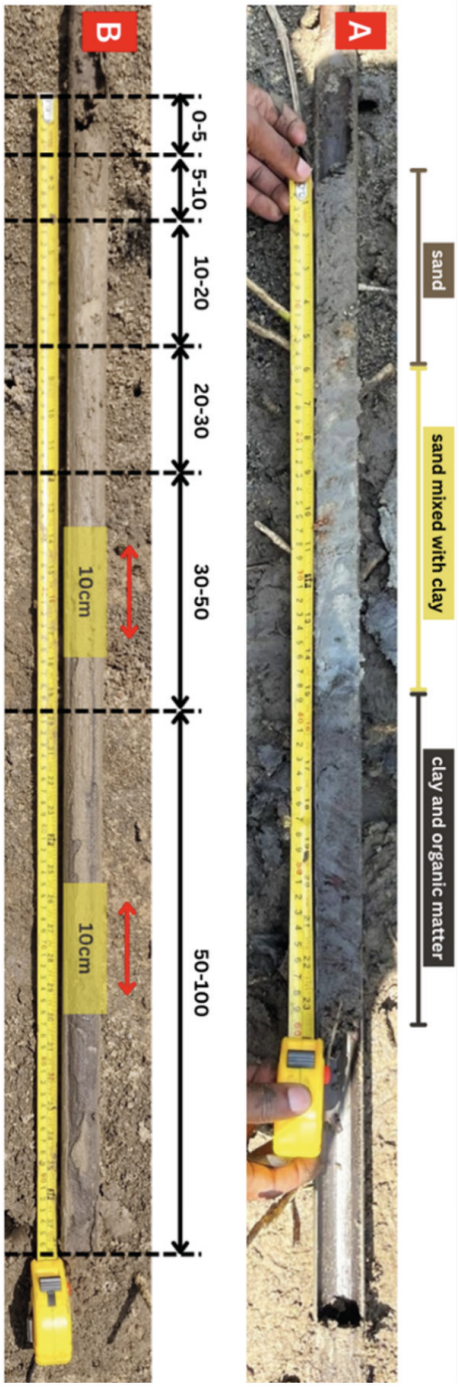

Figure 4. (A) Soil composition gradient along the core; (B) soil sample segments.

D. *Tree measurements*

In each subplot, we identified and counted saplings and seedlings within a 2 m radius from the subplot's center (0.001256 ha). We counted and measured trees with a diameter at breast height (DBH) smaller than 5 cm and trees shorter than 1.37 m (dwarf trees) within the 2 m radius subplot. For dwarf trees, we measured the trunk diameter at 30 cm from the forest floor and recorded the canopy's width, length, and height using a measuring tape to calculate the Canopy Volume. Within a 7 m radius from the subplot's center (0.015386 ha), we identified and measured trees with a DBH above 5 cm and assessed the quality and condition of their trunks (Figure 5). We measured DBH using a diameter tape and a tree caliper. We estimated tree height using the tallest team member (whose height was known) as a reference.

E. *Dead Wood Biomass (or Downed wood)*

We used an aluminum gauge to measure downed wood debris (Figure 6). Along each transect, we tallied each piece of wood debris using the planar intercept technique (Brown, 1974; Kauffman & Donato, 2012), considering wood pieces only if the transect tape intersected their central axis. We recorded a piece multiple times if the tape intersected it more than once (e.g., a fallen tree or long branch). Following the planar intercept technique, we tallied wooden debris by diameter classes along each of the four transects: we counted fine pieces (diameter < 0.6 cm) at the extremities of each transect, from 10 to 12 m from the transect center, as these fine pieces are at greater risk of being trampled and broken by the team setting up the transects. We then tallied small pieces (0.6 – 2.5 cm) from 7 to 10 m from the transect center and medium pieces (2.5 – 7.6 cm) from 2 to 7 m from the transect center. Finally, we tallied large wood pieces (> 7.6 cm) along the entire length of the transect (Figure 6). Additionally, we recorded the state of these largest pieces (sound or rotten) as an indicator of density and measured and recorded their dimensions.

Figure 5. Establishment of subplots, DBH measurement, and height estimation.

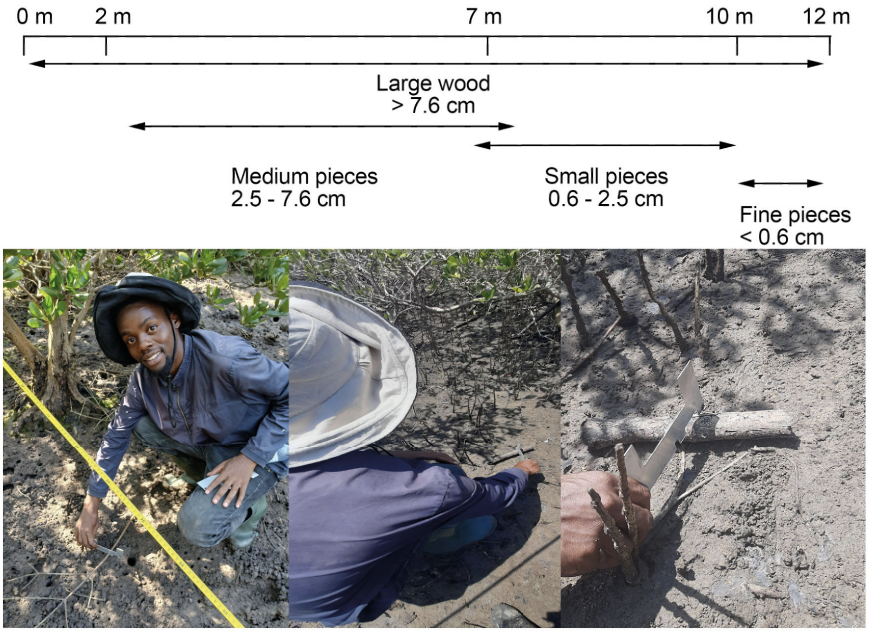

Figure 6. Dead wood debris transect for sampling downed wood using the planar intersect technique from (Kauffman & Donato, 2012).

F. *Tree biomass and carbon stocks calculations*

In each plot, we recorded vegetation information to assess stand structure and calculate aboveground biomass, which we converted into aboveground and belowground C stocks. We calculated above- and belowground tree biomass using specific allometric equations from the literature (Table I). We then converted biomass into C stocks by multiplying by 0.46 (Kauffman & Donato, 2012). We calculated C stocks using the following allometric equation (scaled to 1 ha):

$$\text{C stocks (Mg C)} = \text{biomass} \times 0.46 \qquad \text{(Equation 1)}$$

Table I. Species-specific allometric equations for mangrove species occurring in Mozambique. B represents biomass, DAP is the diameter at breast height, h is the height, and P stands for wood density

Species	**Allometric equations**	**Wood density**
Avicennia marina[1]	$B=0.1848*DAP^{2.3524}$	0.661
Bruguiera gymnorrhiza[2]	$B=0.0464*(DAP)^{0.94275}*p$	0.741
Ceriops tagal[3]	$B=10-7247*DAP^{2.3379}$	0.803
Heritiera littoralis[4]	$B=0.464*(DAP^2*h)^{0.94275}*P$	1.074
Lumnitzera racemosa[4]	$B=0.0214*(DAP*h)^{1.05655}*P$	0.565
Rhizophora mucronata[4]	$B=0.0311*(DAP^2*h)^{1.00741}*P$	0.867
Soneratia alba[4]	$B=0.0825*(DAP^2*h)^{0.89966}*P$	0.780
Xylocarpus granatum[4]	$B=0.0830*(DAP^2*h)^{0.89806}*P$	0.700

1 (Clough & Scott, 1989)

2 (Comley & McGuinness, 2005)

3 (Sinclair et al., 1971)

4 (Kauffman & Cole, 2010)

G. *Structure*

We grouped adult trees by genus and botanical family to analyze floristic composition, presenting the results in a categorical table. We determined phytosociological parameters, frequency, density, dominance,

and importance value index, using the formulas in Table II to analyze phytosociology. We evaluated the condition and quality of forest trees' trunks by grouping them into defined categories, displayed in a bar graph. We classified trees as "Intact", "Partially cut", "Severely cut", "Die back", or "Stump", following the approach used by Kairo et al., (2002) and Bandeira et al., (2009). Additionally, we assessed the quality of the main trunk as Quality I (trees with erect stems, useful for construction), Quality II (trees with semi-erect stems, requiring modification for construction use), or Quality III (trees with crooked stems, not useful for construction). We also classified dwarf trees with stems less than 1 m tall as Quality III.

Table II. Formulas used to analyze the floristic composition.

	Abb.	Formula	Unit
Absolute density	DA	$DA = \frac{n_i}{A}$	n/ha
Relative density	DR	$DR = \frac{DA}{\sum DA} \times 100$	%
Absolute dominance	DoA	$DoA = \frac{g_i}{A}$	m^2/ha
Relative dominance	DoR	$DoR = \frac{DoA}{G} \times 100$	%
Absolute frequency	FA	$FA = \frac{p_i}{P} \times 100$	%
Relative frequency	FR	$FR = \frac{FA}{\sum FA} \times 100$	%
Importance value index	IVI	$IVI = \frac{(DR + DoR + FR)}{3}$	%

Where:
n_i = total number of individuals sampled for each species *i*, per unit area;
i = sampled area (ha);
A = total number of individuals sampled, regardless of species;
N = basal area of each species;
g_i = total basal area of the species found per unit area;
G = number of sampling units with the presence of species *i*;
p_i = total number of sampling units.

IV. Results

A. *Spatial distribution*

The forest composition of the study area was heterogeneous, characterized by tree height and tide gradients. Tree height decreased rapidly from the sea slope to the landward, with interior areas dominated by old-growth stands of low stature and dwarf trees (<1.37 m). We observed *Avicennia marina* at both low and high elevations (Figure 7). Tall, vigorous *Rhizophora mucronata* and *A. marina* dominated the fringe zone. As we moved closer to the forest interior, *Ceriops tagal* and some medium-sized individuals of *Bruguiera gymnorhiza* became dominant.

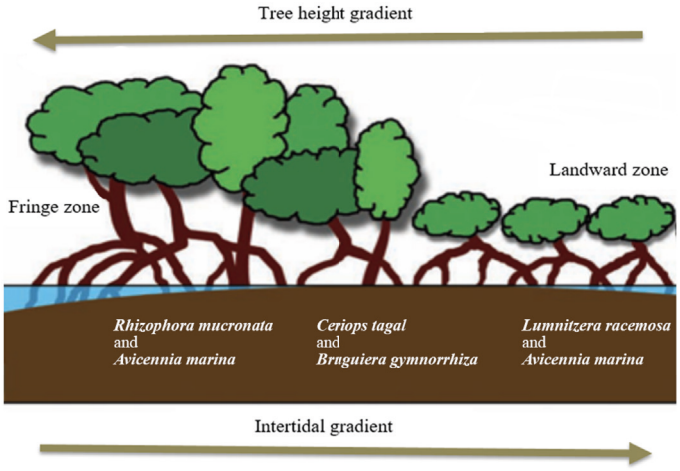

Figure 7. Distinctive tree height and tidal gradient of the study site. Adopted from (Feller et al., 2010).

Table III. Mangrove species composition in Saco along the elevation gradient.

Elev.	Plot	Dominant sp.	Location	Site category
Low	1	*R. mucronata*	Downstream	Forest
	1	*A. marina*	Downstream	Forest
	13	*A. marina*	Middle intertidal area	Forest
	13	*A. marina*	Downstream	Forest
	14	*A. marina*	Middle intertidal area	Forest
Middle	14	*R. mucronata*	Downstream	Forest
	6	*C. tagal*	Upstream, middle intertidal	Forest
	6	*C. tagal*	Middle intertidal area	Forest
	9	*R. mucronata*	Middle intertidal area	Dwarf
High	9	*R. mucronata*	Upstream	Dwarf/ scrub
	0	*C. tagal*	Middle intertidal area	Dwarf/ scruby
	2	*R. mucronata*	Middle intertidal area	Dwarf
	2	*R. mucronata*	Upstream	Shruby

High	3	*R. mucronata*	Upstream	Dwarf
	3	*C. tagal*	Middle intertidal area	Dwarf/ scrub
	4	*A. marina*	Upstream, high intertidal	Dwarf
	4	*A. marina*	Upstream intertidal	Dwarf
	5	*L. racemosa*	Upstream, edge of the forest	Dwarf
	5	*L. racemosa*	Upstream, edge of the forest	Scrub

B. *Forest structure*

We sampled a total of 427 adult trees, belonging to five species. We calculated the average tree density for each species as follows: *C. tagal* (10,464 trees/ha), *A. marina* (7,734 trees/ha), *R. mucronata* (7,019 trees/ha), *L. racemosa* (2,015 trees/ha), and *B. gymnorrhiza* (520 trees/ha).

The average forest density varied by stratum (Table IV), with the low elevation stratum showing a higher density (1,689 trees/ha) than the medium (1,571 trees/ha) and high (1,219 trees/ha) strata. C. *tagal* (6,954 trees/ha) and R. *mucronata* (4,420 trees/ha) dominated the low elevation stratum (Table IV). C. *tagal* (3,445 trees/ha), and A. *marina* (3,380 trees/ha) characterized the middle stratum. C. *tagal* (3,445 trees/ha), A. *marina* (2,795 trees/ha), and L. *racemosa* (3,380 trees/ha) characterized the high stratum.

Table IV. Species density (tree/ha) according to the elevation gradient. Average ± standard error.

Species	Low	Middle	High	Total
C. *tagal*	6,954±484	3,445±870	65±28	10,464±681
A. *marina*	1,560±241	3,380±650	2,795±849	7,734±611
R. *mucronata*	4,420±431	2,600±464	-	7,019±448
L. *racemosa*	-	-	2,015±529	2.015±326
B. *gymnorrhiza*	520±86	-	-	520±66
Average	1,682±529	1,571±1157	1,219±531	

Tree dominance varied by stratum, decreasing with increasing elevation. We observed that *A. marina* and *R. mucronata* dominated across the three strata compared to other species (Table V).

Table V. Species dominance (m^2/ha) according to the elevation gradient. Average ± standard error.

Species	Low	Middle	High	Total
A. *marina*	67,653±10,897	35,374±9,119	8,141±3,120	111,168±9,424
R. *mucronata*	86,569±6,529	23,206±4,615	-	109,775±7,096
C. *tagal*	34,950±2,875	13,999±2,819	0,011±0,005	48,961±3,036
B. *gymnorrhiza*	14,151±2,002	-	-	14,151±1,506
L. *racemosa*	-	-	5,456±1,960	5,456±1,084
Average	25,415±9,167	12,097±10,379	3,402±2,830	

Avicennia marina, R. mucronata and C. *tagal* share the ecological importance in the forest (Figure 8), which as around 30% for each. These species are highly represented throughout the forest and make significant contribution to its ecological functioning.

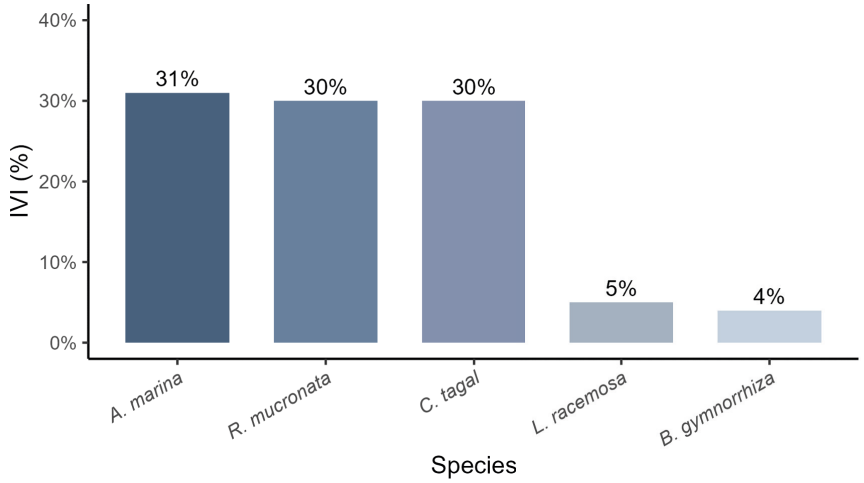

Figure 8. Importance Value Index (IVI) of the mangrove forest of Saco da Inhaca.

Figure 9 displays the diameter size-class distribution per species. We observed that the tree population in the mangrove forest of Inhaca Island exhibits a J-inverted diametric distribution curve typical of natural forests, where tree density decreases as tree size increases, following a geometric progression.

The populations of *A. marina*, *C. tagal*, and *R. mucronata* show a distribution typical of natural forests, whereas the populations of *L. racemosa* and *B. gymnorrhiza* deviate from this expected curve. A possible explanation is that *L. racemosa* grows only on the upper side of the forest, where high salinity stunts tree growth. In contrast, *B. gymnorrhiza* is sparsely distributed throughout the forest, particularly in areas with high canopy cover, where propagules struggle to establish due to competition for light.

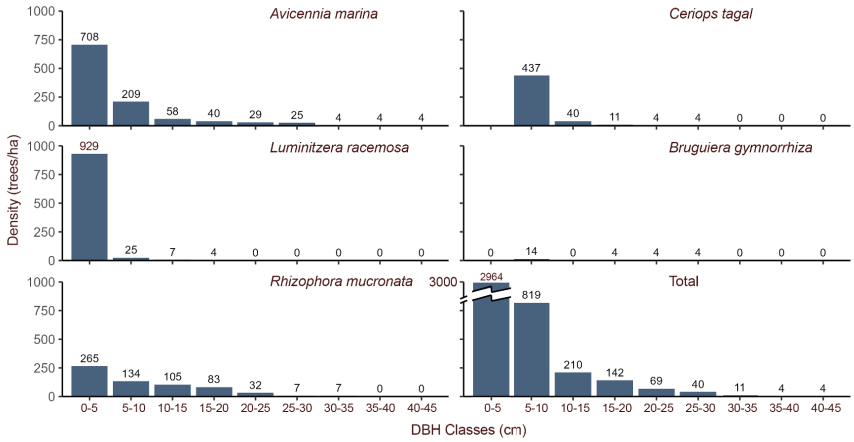

Figure 9. Diameter at Breast Height (DBH) class distribution of individual mangrove species and the total community at Saco de Inhaca. The y-axis represents tree density (individuals per hectare), and the x-axis indicates DBH classes (cm). All subplots share uniform y-axis limits (0–1000 trees/ha) to allow visual comparison across species. In the "Total" panel, the first bar (DBH class 0–5 cm) exceeds the axis range and is represented as a truncated (broken) bar, with the actual value indicated.

C. *Stem quality and condition*

Most mangrove trees are crooked and thus unsuitable for construction, leading to their use primarily for firewood and charcoal. Crooked trees typically occur in areas with high salinity and poor soils, or as a result of selective mangrove logging. At Inhaca, we observed that crookedness appears to be a natural condition, as stumps were not abundant in the forest. Additionally, since most trees are crooked and thin, mangrove logging does not pose a significant issue in this forest.

The results of the study also show that the vast majority of the trees are intact or partially cut. Severely cut trees are rare, occurring at similar densities and with dwarf trees.

D. *Biomass and carbon*

We found that trees contributed the largest amount of aboveground biomass compared to other pools: trees stored an average of 67.83 ±

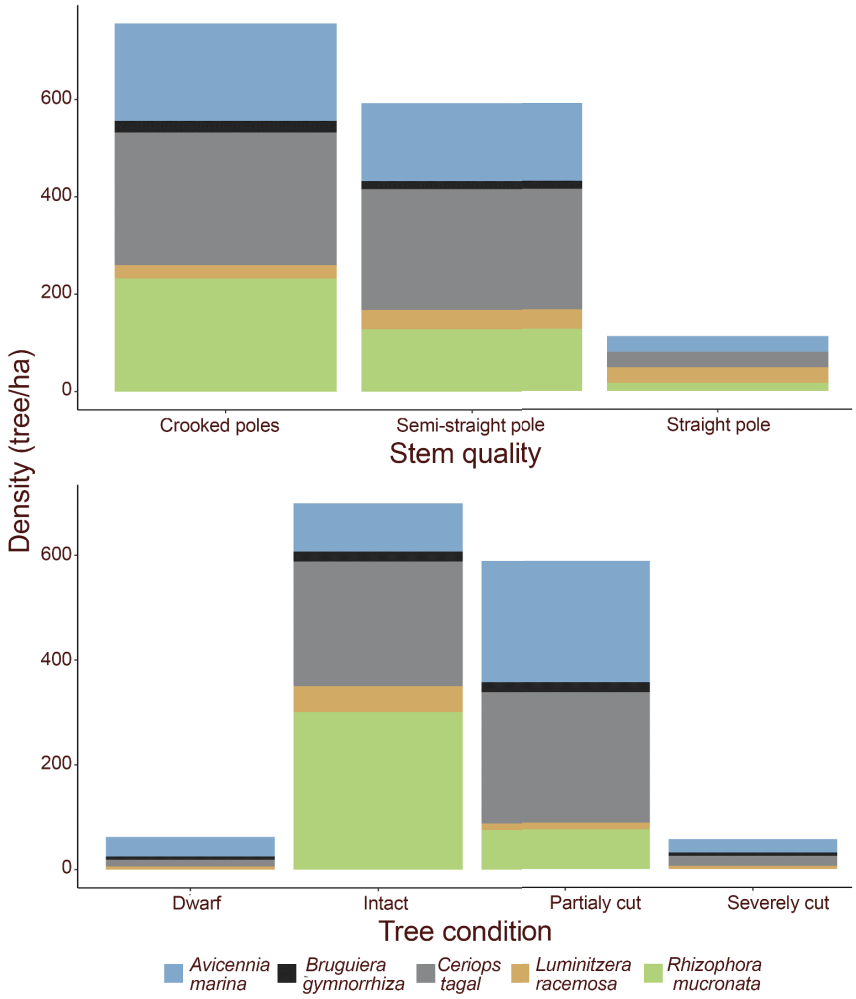

Figure 10. Stacked barplots showing the density (trees per hectare) of mangrove species by stem quality (top) and tree condition (bottom).

51.66 Mg/ha, while woody debris stored 5.27 ± 5.94 Mg/ha (Table VI). Our assessment of biomass and carbon storage across different plots in the mangrove forest of Saco Bay, Inhaca, revealed significant variability in both aboveground and belowground components. These variations were influenced by species composition, distance from the coastline, and forest density.

Site	Species	Aboveground		Belowground		Downed Wood	
		Biomass	C stock	Biomass	C stock	Biomass	C stock
Plot 0	BG-CT-RM	217.86 ± NA	108.93 ± NA	115.36 ± NA	44.99 ± NA	5.23 ± NA	2.61 ± NA
Plot 1	CT-RM	114.63 ± 94.85	57.79 ± 48.10	49.25 ± 38.58	19.21 ± 15.04	32.61 ± 21.23	16.31 ± 10.61
Plot 2	AM-CT-RM	29.64 ± 17.46	14.82 ± 4.79	20.48 ± 8.01	7.99 ± 3.12	5.13 ± 6.46	2.57 ± 3.23
Plot 3	AM-CT-RM	114.06 ± 114.70	57.03 ± 57.35	75.14 ± 78.29	29.31 ± 30.53	0.87 ± 0.44	0.44 ± 0.22
Plot 4	AM-CT	24.04 ± 29.23	12.02 ± 14.61	13.61 ± 16.18	5.31 ± 6.31	15.31 ± 19.22	7.66 ± 9.61
Plot 5	LR	16.12 ± 18.94	8,06 ± 9,47	10.08 ± 11.33	3.93 ± 4.42	12.98 ± NA	6.49 ± NA
Plot 6	AM-BG-CT-RM	276.58 ± 1.03	138,29 ± 0,52	144.44 ± 30.88	56.33 ± 12.04	5.36 ± 5.91	2.68 ± 2.96
Plot 9	CT-RM	139.86 ± 75.43	69.93 ± 37.72	64.98 ± 29.60	25.34 ± 11.54	8.12 ± 1.90	4.06 ± 0.95
Plot 13	AM-CT-RM	239.02 ± 34.16	119.51 ± 17.08	161.76 ± 40.37	63.09 ± 15.74	10.24 ± 12.90	5.12 ± 6.45
Plot 14	CT-RM	255.03 ± 0.69	112.52 ± 0.35	102.41 ± 0.12	39.94 ± 0.05	5.07 ± 0.27	2.54 ± 0.13
TOTAL	All	135.57 ± 103.27	67.83 ± 51.66	73.67 ± 59.07	28.73 ± 23.03	10.54 ± 11.88	5.27 ± 5.94
Biomass	All						303.08 Mg
C stock	All						140.27 Mg

Table VI. Values of biomass and carbon stock estimated per plot at Saco de Inhaca for each ecosystem component (aboveground, belowground, and downed wood), expressed in Mg/ha (mean ± standard deviation). Data are presented by plot and associated species composition. The bottom row of each component section shows the across plots for that component. The last two rows represent the total biomass and carbon stock per component, summed (not averaged) across all plots. Mg/ha stands for megagrams per hectare, equivalent to metric tons per hectare. RM = *Rhizophora mucronata*, AM = *Avicennia marina*; CT = *Ceriops tagal*, BG = *Bruguiera gymnorrhiza*; LR = *Lumnitzera racemosa*. Saco mangrove forest total area: 91 ha (Neukermans & Koedam, 2014).

E. *Biomass distribution*

We observed that total aboveground biomass (AGB) varied markedly across the surveyed plots. In plots farther from the sea, such as Plot 2 and Plot 4, we found relatively low AGB values, particularly for *Avicennia marina* (Am) and *Ceriops tagal* (Ct), which exhibited sparse and stunted growth. In these plots, AGB ranged from 20.51 Mg/ha in Plot 5.1 to 22.86 Mg/ha in Plot 2.1. Belowground biomass (BGB), representing the root systems, was also limited in these areas, underscoring the reduced biomass contributions from these species at the forest edge.

Conversely, in more interior plots like Plot 1.1, Plot 9.1, and Plot 13, which are closer to a large tidal channel, we recorded significantly higher AGB and BGB values. In these plots, AGB peaked at 275.85 Mg/ha in Plot 13.2, while Plot 13.1 recorded 263.17 Mg/ha, indicating a dense and mature mangrove stand. The BGB in these regions also contributed substantially, particularly in Plot 13.2, where it reached 131.59 Mg/ha, highlighting the role of root systems in carbon sequestration in more established forest zones.

F. *Carbon Stock*

We found that patterns in carbon storage mirrored those observed for biomass, with aboveground carbon (AGC) and belowground carbon (BGC) showing considerable variation across plots. In the less dense, outer-edge plots (e.g., Plot 2.1 and Plot 5.1), we measured low carbon storage in aboveground biomass, with AGC values of 11.43 Mg/ha and 14.75 Mg/ha, respectively. Belowground carbon contributions were similarly modest in these regions, reflecting the limited root biomass.

Conversely, in plots closer to the tidal channel, such as Plot 13.2 and Plot 9.1, we observed a substantial increase in carbon storage. Plot 13.2 exhibited an AGC of 138.65 Mg/ha, with BGC reaching 64.85 Mg/ha, the highest among all surveyed plots. These values indicate that denser and more mature mangrove stands near water sources are key contributors to carbon sequestration in the ecosystem.

G. *Wood debris contribution*

Wood debris biomass (WDB), although generally lower than AGB and BGB, played a non-negligible role in the overall carbon stock, particularly in plots with mature forests. Plot 13.2, for instance, recorded 74.22 Mg/ha of carbon in wood debris, indicating that deadwood and fallen branches also significantly contribute to carbon sequestration, especially in mature and dense mangrove stands.

H. *Species-specific contributions*

Species-wise, *Rhizophora mucronata* (Rm) exhibited the highest contributions to both aboveground and belowground biomass in most interior plots (Figure 11). For example, in Plot 13, R. *mucronata* showed AGB values exceeding 4 Mg and BGB values of over 2 Mg. Similarly, in terms of carbon stock, R. mucronata consistently outperformed other species, particularly in the interior plots where it thrives in more water-rich environments.

Avicennia marina (Am) and *Ceriops tagal* (Ct), on the other hand, contributed lower biomass and carbon values, particularly in the edge plots (e.g., Plot 2 and Plot 4), where environmental conditions are less favorable for robust growth.

V. Discussion

A. *Species spatial distribution*

We observed a clear species zonation pattern in the study area, with *A. marina* occupying the upper and lower parts of the intertidal gradient, *R. mucronata* near riverbanks and in lower, frequently inundated areas, and *C. tagal* in intermediate areas. Previous research has shown that species composition in mangrove forests is influenced by salinity, tidal flooding frequency, and nutrient availability, all of which vary along the elevation gradient (Lovelock & Ellison, 2007; Spalding et al., 2010). The distribution patterns of *A. marina, C. tagal*, and *R. mucronata* we

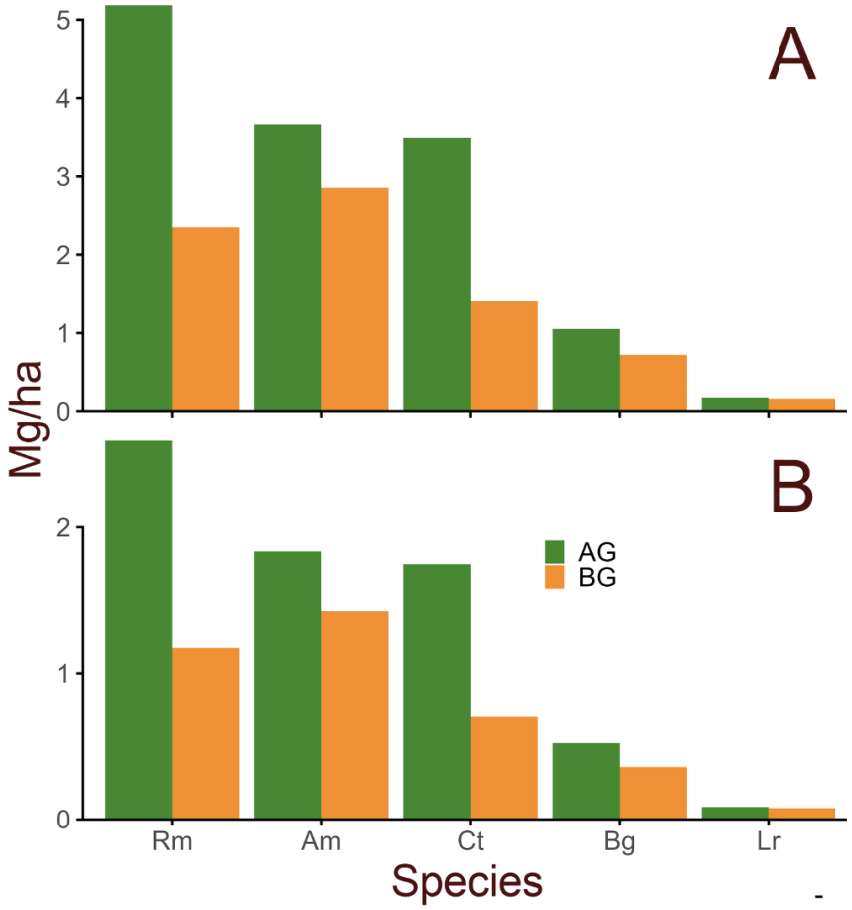

Figure 12. (A) Biomass and (B) carbon quantification per species. AG: Aboveground; BG: Belowground; Rm = *Rhizophora mucronata*, Am = *Avicennia marina*; Ct = *Ceriops tagal*, Bg = *Bruguiera gymnorrhiza*; Lr = *Lumnitzera racemosa*.

observed in this study align with the ecological dynamics of natural forests in Mozambique and several coastal regions of Africa (Bandeira & Paula, 2014; Bosire et al., 2008).

B. *Forest structure*

In the low-elevation stratum, we observed that trees benefit from proximity to the channel, which brings frequent tidal inundation and a source of nutrients, as well as lower salinity. These conditions favor the growth of salt-sensitive species such as *C. tagal* and *R. mucronata* (Kathiresan & Bingham, 2001). In the high-elevation stratum, where salinity is significantly higher, we found that stunted *A. marina* dominates. In contrast, *L. racemosa* alone grows at the terrestrial margin, where inundation rate and nutrient availability is lower, and salinity substantially higher (Feller et al., 2010; Guo et al., 2011).

We found that the structural attributes of this forest align with those reported in other studies for the Maputo Bay area, including past studies at Saco (Amade et al., 2019; Bandeira et al., 2009; Machava-António et al., 2022). Compared to, for instance, the Zambezi Delta (Trettin et al., 2016), Saco is a relatively small forest in terms of tree height and diameter. This may be because Maputo Bay is in a subtropical area near the natural limit of mangrove occurrence in southern Africa. Moreover, southern Mozambique has a characteristic dune coast, resulting in low nutrient input from rivers and sandier soils. These conditions do not favor the establishment and full development of mangrove forests. However, the unique position of Inhaca Island within Maputo Bay creates suitable conditions for the development of small mangrove patches, which have grown to reasonable sizes, comparable to other forests in the Western Indian Ocean region (Bosire et al., 2008; Kairo et al., 2002).

C. *Stem quality and condition*

We observed that crooked stems dominate the forests in nearly all subplots, suggesting that commercial exploitation of mangrove wood is limited (Alongi, 2002; Bandeira & Paula, 2014). This tree physiognomy may result from selective logging or the natural outcome of local environmental conditions, such as low temperatures, high salinity, and nutrient-poor shallow soils. At Saco, we found it likely that environmental conditions are the primary cause, as mangrove logging

is strictly prohibited, and we observed very few stumps during data collection. Additionally, local communities reported to us that they prefer collecting dry branches for firewood, demonstrating a conservation strategy that prioritizes preserving the structural integrity of mangroves, thereby enhancing their ecological resilience and the provision of environmental services (Bamford et al., 2017; Lovelock et al., 2015).

D. *Biomass and carbon stocks*

The findings from the Saco Bay mangrove forest in Inhaca highlight the substantial role that this ecosystem plays in carbon sequestration and biomass storage, both in terms of local ecological dynamics and in the broader national context of Mozambique's mangrove forests.

E. *Biomass and carbon stocks*

We found that aboveground biomass (AGB) constitutes the largest proportion of total biomass in Saco Bay, averaging 135.57 Mg/ha, equivalent to 67.83 Mg C/ha in carbon stock. These figures align with the general trend in mangrove ecosystems, where aerial roots, branches, and trunks contribute significantly to carbon storage. In comparison, belowground biomass (BGB), though lower in magnitude (73.67 Mg/ha, 28.73 Mg C/ha), plays an equally critical role, particularly due to its permanence and stability as a carbon sink. Mangrove root systems sequester carbon more durably than aboveground biomass, as frequent root renewal due to seawater exposure and slow decomposition in waterlogged soils enhance long-term carbon storage in both roots and soil.

Deadwood biomass, while a smaller fraction of the total biomass (10.54 Mg/ha with a carbon stock of 5.27 Mg C/ha), remains significant. Deadwood plays a transitional role, slowly releasing carbon back into the environment while supporting soil carbon inputs and microbial activity. The presence of downed wood in mangrove ecosystems like Saco Bay enhances both carbon storage and habitat complexity, thus supporting biodiversity. We observed a higher presence of deadwood in marginal plots, such as Plot 4, which may be linked to anthropogenic management. Specifically, we noted that wood harvesting in the area

is predominantly sustainable: only large, straight poles are removed, while most smaller branches are left on the ground, serving as a source of beneficial organic matter for the surrounding ecosystem. Plots near the edge of the mangrove forests, being closer to the village, are more accessible and thus more susceptible to cutting, likely explaining the abundance of deadwood in these areas.

We estimated the total carbon of the system at 140.27 Mg/ha. This figure excludes soil carbon, which is the largest carbon pool in the system, suggesting that Saco's actual carbon storage capacity is much higher. Soil carbon accounts for 62–99% of the total carbon in the system, and based on these averages, we anticipate that soil carbon in Saco could be approximately 438.34 Mg C/ha (Kauffman & Donato, 2012). Nevertheless, the total carbon estimated for Saco falls within the global range of 55–1376 Mg C/ha (Howard et al., 2014). In Mozambique, total carbon at the Limpopo estuary was estimated between 240.2 Mg/ha and 362.3 Mg/ha (Da Costa & Macamo, 2023). Other global estimates include 853.2 Mg/ha and 1311.6 Mg/ha in tropical mangroves of Indonesia (Taberima et al., 2014), and 234.9 ± 39.16 Mg C/ha and 106.23 Mg C/ha in temperate mangroves of South Africa (Johnson et al., 2020), and New Zealand (Bulmer et al., 2016), respectively.

F. *Species-specific contributions to biomass and carbon stock*

Our findings show that *R. mucronata* contributes the most to both biomass and carbon stocks. As this species dominates along channels and at the seafront, exposure to currents promotes the washing away of fine particles, resulting in more aerated soils. The increased oxygenation accelerates decomposition and mineralization of organic matter, enhancing nutrient uptake by the trees and contributing, along with lower salinity, to their greater height and biomass. The aboveground biomass of *R. mucronata* reaches notable values, indicating its high structural development compared to other species like *A. marina* and *C. tagal*, which are smaller in stature and often more prevalent throughout the entire mangrove stand, especially in edge plots (e.g., Plot 2 and Plot 4).

In areas closer to human activity, such as village-proximate plots (2 and 4), our observations indicate that the dominance of *A. marina* and

C. tagal, both exhibiting mainly dwarf forms, reflects possible anthropogenic impacts and harsher environmental conditions. These two species are highly adaptable to challenging conditions, though they have lower carbon storage capacity per unit area compared to *R. mucronata*. Our results highlight the importance of considering species composition when assessing carbon sequestration potential within mangrove ecosystems.

VI. Management recommendations

Although the current state of the forest supports high carbon and biomass storage capacity, we cannot exclude future environmental and anthropogenic pressures that will need proactive management measures. Here, we outline recommendations aimed at maintaining the ecological integrity of the area and enhancing its role in climate mitigation.

Establish long-term monitoring programs. Our findings emphasize that, given the dynamic nature of mangrove ecosystems and their sensitivity to environmental changes, a robust long-term monitoring program is essential. Regular monitoring of biomass, carbon stocks, and forest health indicators will provide valuable data on ecosystem changes over time. Our recommendations include focusing monitoring efforts on forest structure, biomass, anthropogenic impacts, and climate-related variable. Mapping and change detection were not covered in this study, although it is highly recommended to understand forest dynamics and conservation status.

Implement controlled access and sustainable harvesting. Our observations indicate that, although the mangroves of Saco Bay are in relatively good condition, the risk of increasing cutting pressure highlights the need to regulate access to forest resources. Our recommendations include establishing controlled access points or designated harvesting zones as well as a restoration program. Additionally, adopting guidelines for the sustainable harvesting of wood and non-wood resources will ensure the long-term maintenance of the forest in good ecological condition.

Strengthen community engagement and awareness. Our findings highlight that local communities play a vital role in the stewardship

of mangrove forests. By enhancing community involvement in management efforts, our recommendations promote the adoption of sustainable use practices. Community engagement can be strengthened through educational programs and community-based monitoring initiatives.

Develop climate adaptation strategies. Our analysis underscores that mangroves are particularly vulnerable to climate change impacts, such as rising sea levels, increased salinity caused by lower rainfall, and extreme weather events, making adaptive management strategies essential. Our recommendations include implementing mangrove restoration and establishing buffer zones to enhance resilience.

Establish a climate resilience and adaptation fund. Our findings suggest that establishing a dedicated fund would support the long-term sustainability of mangroves in Saco Bay and other critical areas. This fund could finance monitoring, community engagement, and restoration efforts, particularly to address climate-driven impacts such as cyclones and droughts. Our recommendations include exploring potential funding sources, such as international climate finance, payments for ecosystem services, and carbon credit programs focused on mangrove conservation.

VII. Conclusions

The Saco Bay mangrove forest on Inhaca Island represents a highly valuable ecological system where environmental conditions significantly shape species distribution and forest structure. Our observations reveal that the predominant presence of species such as *Rhizophora mucronata*, *Avicennia marina*, and *Ceriops tagal* reflects their adaptability to varying levels of salinity, tidal influences, and soil conditions, with clear stratification between low- and high-elevation zones. These characteristics contribute to a high biomass and carbon storage capacity, placing the Saco Bay mangrove forest well above the national average in carbon reserves.

Despite the limited economic value of the wood, our findings indicate that local communities use the forest sustainably, recognizing its

ecological importance. This ecosystem, with its high biomass density and carbon reserves, significantly contributes to regional and national carbon conservation efforts. Consequently, its protection is vital not only for maintaining ecosystem services but also for supporting Mozambique's international climate commitments.

Our recommendations stress that proactive management measures are essential to ensure the long-term preservation of the Saco Bay mangrove forest, involving local communities and integrating mangrove conservation into national policies. Combining regular monitoring, controlled access to resources, and climate adaptation strategies will sustain the ecological health of this ecosystem, ensuring it continues to provide climate and ecological benefits for future generations.

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Mangrove forests, like this one in Saco Bay, thrive in coastal intertidal zones. Their intricate aerial roots create habitats for wildlife, stabilize soils, and store carbon, making them vital for coastal ecosystems (photo by Paolo Ramoni-Perazzi).

TERRESTRIAL MAMMALS OF INHACA ISLAND
MONITORING THEIR OCCURRENCE THROUGH NON-INVASIVE METHODS

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Abstract: Mozambique's mammalian fauna forms a vital component of the country's biodiversity, yet documentation for Inhaca Island remains limited. Knowledge gaps regarding vertebrate use of mangrove ecosystems create challenges for conserving many priority species. To address this, we conducted a preliminary survey of terrestrial mammals in Inhaca Island's mangroves. Our study aimed to introduce students to analyzing mammalian species richness, Relative Abundance Index (RAI), and Shannon diversity across three mangrove ecosystems on Inhaca Island—Ponta Rasa, Saco Bay, and Noge. We collected data using non-invasive methods, including camera trapping and footprint recording along transects, to identify medium- and large-sized mammal species. We documented representatives from three mammalian Orders (Carnivora, Primates, and Rodentia), encompassing six Families (Felidae, Herpestidae, Mustelidae, Hominidae, and Muridae). We identified four species: *Felis catus*, *Atilax paludinosus*, *Aonyx capensis*, and *Homo sapiens*. Additionally, we observed individuals from the family Muridae, though we could not identify them to the species level. We recorded five species in Ponta Rasa, one in Saco, and none in Noge. Carnivora emerged as the order with the highest number of families and species. Our analysis of relative abundance showed

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uneven distribution of mammal species across the three mangrove sites (Kruskal-Wallis Test, df = 2, $p < 0.05$; Dunn's *post hoc* test). We found *A. paludinosus* to be the most widespread species, with a relative abundance of 100% in Saco and 48.05% in Ponta Rasa. The Shannon index revealed higher diversity in the Ponta Rasa mangrove ($H' = 1.501$). These findings highlight the ecological importance of Inhaca Island's mangroves in supporting the activities of the recorded mammal species. Although preliminary, our results demonstrate higher diversity in Ponta Rasa, underscoring the need for targeted conservation efforts, particularly for the mangrove ecosystems in this area. We consider these results preliminary and recommend following the suggestions outlined in the text.

Keywords: Diversity, Mammals, Mangroves, Inhaca Island, Indirect Sampling Methods.

I. Introduction

Mammals in Mozambique form a key part of the country's biodiversity, yet information about them remains scarce. Despite the diverse range of mammals in Mozambique, many aspects of their presence and distribution remain undocumented and poorly understood (Neves et al., 2018). The known diversity of terrestrial mammals in Mozambique likely underestimates the true extent, even with a 14% increase in documented species compared to earlier records (Neves et al., 2018). Documentation of this biodiversity, especially in less-explored northern regions and coastal islands like Inhaca Island, remains limited.

Situated in Maputo Bay, southern Mozambique, Inhaca Island plays a critical role in conserving insular mammalian biodiversity. Mangrove forests decline faster than tropical rainforests and coral reefs, yet global conservation efforts prioritize the latter ecosystems (Rog et al., 2017). While degradation of mangrove systems raises significant concern, their role as marine environments overshadows their function as terrestrial ecosystems, such as providing forest resources for human use and habitat for terrestrial fauna, which often goes overlooked (Rog et al., 2017).

Terrestrial species inhabiting mangrove ecosystems face distinct environmental challenges, including frequent tidal inundation, unpredictable storm surges, anaerobic soil conditions, and high salinity levels, which differ from those found in inland habitats (Luther & Greenberg,

2009). Assessing the structure of the terrestrial mammal community on Inhaca Island is essential for understanding the ecological importance of this insular ecosystem and crafting effective conservation strategies. Mangrove-dwelling mammals often participate in complex trophic networks that connect terrestrial and marine ecosystems, and their activities significantly impact soil quality and habitat structure (Mohd-Taib et al., 2021).

Limited knowledge about vertebrate use of mangrove ecosystems creates challenges for conserving numerous priority species (Rog et al., 2017). To tackle this, we carried out a preliminary survey of terrestrial mammals in Inhaca Island's mangroves using non-invasive methods. Our goals were to: (1) determine the species richness of terrestrial mammals; (2) measure their relative abundance; and (3) analyze the Shannon diversity index across different mangrove ecosystems.

II. Materials and methods

A. *Study area*

We conducted our study on Inhaca Island, located in the Indian Ocean approximately 32 km east of Maputo, the capital of Mozambique, at 26°S latitude and 33°E longitude, covering an area of 40 km² (Kalk, 1995; Figure 1). Inhaca Island lies in a transitional zone between tropical and warm subtropical climates (Kalk, 1959), at the interface between the shallow waters of Maputo Bay and the open Indian Ocean, with mangroves extending along the sheltered bays of the southern and northern coasts (de Boer, 2002).

Location of the study area. *Left*: Inhaca Island, showing transects (white dashed lines), photo-trapping stations (yellow points), and footprint tracking points (red points). *Lower right*: Location of Inhaca Island (white arrow) within Maputo Bay, southern Mozambique. *Upper right*: Location of Mozambique on the African continent. Projection: Universal Transverse Mercator Zone 36S. Datum: WGS 1984. Data source: CENACARTA.

The region experiences a humid tropical climate, with an average annual temperature ranging between 18°C and 26°C (Macnae & Kalk, 1962). The mangrove forests of Inhaca Island provide a variety of tree-associated microhabitats (hereafter TreMs), supporting a diverse array of species. The mangroves on Inhaca Island receive no direct freshwater influence (de Boer, 2002).

B. *Sampling design and data collection*

We sampled terrestrial mammals using non-invasive methods to minimize impacts on the species. We placed until ten camera traps strategically at various locations within the mangrove ecosystems to capture images of animals automatically. The camera traps were Browning Strike Force HD Pro X (20MP), infrared flash (BTC-5HDPX) with a built-in viewer, to monitor the area (Figure 2). We installed nineteen camera trap stations across three distinct regions of the mangrove ecosystem: Ponta Rasa (10), Saco Bay (6), and Noge (3). We mounted these camera traps on mangrove tree trunks to photograph predominant mammals in the ecosystem (Figure 2) (Sharma et al., 2020). To increase our chances of obtaining photographic records for this study,

Figure 2. Installation of camera traps: (A) Selection of the site and camera trap programming; (B) Recording of geographic coordinates; (C) Installation of the camera trap and recording of relevant data; (D) Camera trap in operation.

Figure 3. Fieldwork using indirect evidence: (A) active search for tracks and scats, with recording of all relevant information; (B) photographic documentation and measurement of a marsh mongoose (*Atilax paludinosus*) track; (C) preparation of a track cast using plaster; (D) collection and recording of scats.

camera traps were deployed in each mangrove from October 02 to October 14, 2025, without students' participation. We temporarily removed the traps and later reinstalled them with the students as part of a hands-on learning exercise to familiarize them with camera-trapping techniques. After an additional 48 hours, we removed the traps again. We considered photographs taken at one-hour intervals as independent photographic events (Soto-Werschitz et al., 2023) and used them to calculate species' relative abundance and compare mammal diversity among the mangrove sites.

We complemented monitoring by systematically tracking footprints, scat, and other indirect signs of presence to gather supplementary information on species distribution and space use (Figure 3). To familiarize ourselves with this approach, we surveyed a 2.1 km transect in the Ponta Rasa mangrove and a 1.9 km transect in the Saco mangrove (Figure 1). We measured footprints with a caliper, created plaster casts for selected tracks, and collected fecal samples in plastic bags. We identified species using a regional field guide (Stuart & Stuart, 2015). We recorded all relevant coordinates using a Garmin GPS XZ.

This combination of non-invasive techniques ensured an efficient and ethical sampling process, enabling us to collect relevant data for analyzing mammal diversity and abundance without disturbing their natural behavior.

C. *Data processing*

We compiled a comprehensive list of all species recorded at each mangrove site and identified each one to the lowest possible taxonomic level. We calculated the relative abundance of each species across Inhaca Island. To compare diversity among the three mangrove sites, we applied the Shannon-Wiener Index. We analyzed differences in species abundance using a Kruskal-Wallis test, followed by Dunn's *post hoc* test. We performed all calculations using the equations described below:

a) Relative abundance (expressed as a percentage):

$$\mathcal{P}_i = (N_i/N_{total}) * 100 \quad \text{(Eq. 1)}$$

Where:
$\mathcal{P}_i$ = relative abundance of the species *i*.
N_i = number of individuals of species *i*.
N_{total} = total number of individuals of all species counted in the area.

b) Shannon index:

$$H' = \Sigma p_i * ln p_i \quad \text{(Eq. 2)}$$

Where:
$\mathcal{P}^i$ = relative abundance of the species *i*.
N_i = number of individuals of species *i*.
N_{total} = total number of individuals of all species counted in the area.

III. Results

A. *Mammal species richness*

Both methods enabled us to identify five mammalian species from five families across three orders (Table I; Figure 4). We documented five species at Ponta Rasa, one species at Saco, and none at Noge. Carnivora displayed the greatest number of families and species.

Table I. List of mammal species recorded at each mangrove in the Inhaca Island during.

	Ponta Rasa	Saco	Noge
Carnivora			
Felidae			
Felis catus	x		
Herpestidae			
Atilax paludinosus	x	x	
Mustelidae			
Aonyx capensis	x		

Primata			
Hominidae			
Homo sapiens	x		
Rodentia			
Muridae			
Unidentified	x		

B. *Relative abundance of mammal species*

We observed low frequencies for all five mammalian species recorded on Inhaca Island: marsh mongooses (*Atilax paludinosus*: 39 records), small rodents (family Muridae: 26), house cat (*Felis catus*: 11), people (*Homo sapiens*: 2), and African clawless otter (*Aonyx capensis*: 1). Consequently, we determined that *A. paludinosus* had the highest relative abundance (49.4%), followed by Muridae (32.9%), house cat (13.9%), local people (2.5%), and *A. capensis* (1.2%) (Figure 5).

We found mammal species unevenly distributed across the three mangrove sites. *Atilax paludinosus* was the most widespread species, with a relative abundance of 100.0% in Saco and 48.1% in Ponta Rasa, possibly indicating its presence in multiple areas and suggesting ecological flexibility (Figure 5). All other species were detected exclusively -at Ponta Rasa. Notably, we recorded no species at Noge, indicating a lack of detectable mammal activity during the sampling period (Figure 5). During this period, we detected *Aonyx capensis* only once, confirming its identification based on the associated footprint.

Relative abundance (%) of mammal species detected through camera trapping or tracks in the mangroves of Inhaca Island, and the overall total. The Noge mangrove is omitted, as no mammal activity was recorded there.

C. *Comparison of diversity among the three mangrove sites*

Species diversity was highest at Ponta Rasa (H' = 1.501). In contrast, both Saco and Noge showed zero values for the Shannon-Wiener index (H' = 0).

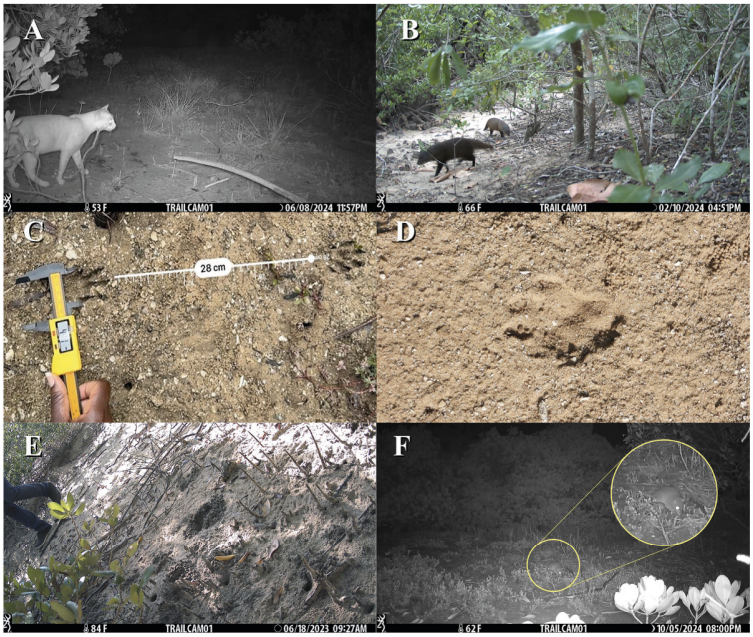

Figura 4. Mammal species recorded at Inhaca Island mangroves through camera trapping (A–B, E–F) and tracks (C–D). (A) House cat (*Felis catus*); (B) A couple of marsh mongooses (*Atilax paludinosus*); (C) Marsh mongoose track measurement; (D) African clawless otter (*Aonyx capensis*) track; (E) A fisherman (*Homo sapiens*); (F) An unidentified rodent (Muridae).

IV. Discussion

We found a disparity in mammalian species richness among the surveyed mangrove sites, with species diversity notably concentrated in Ponta Rasa and a concerning absence of detections at Noge. Comparative studies in well-preserved habitats typically report higher mammalian diversity, suggesting that our study area may be undergoing some degree of ecological degradation (Begon et al., 2006).

Field observations further support this pattern: we noted that Ponta Rasa exhibited lower levels of anthropogenic disturbance, particularly in comparison to Saco. This reduced human influence may partially account for the higher number of mammal species recorded at Ponta Rasa. However, in addition to human impact, other ecological and environmental variables must be considered. Structural

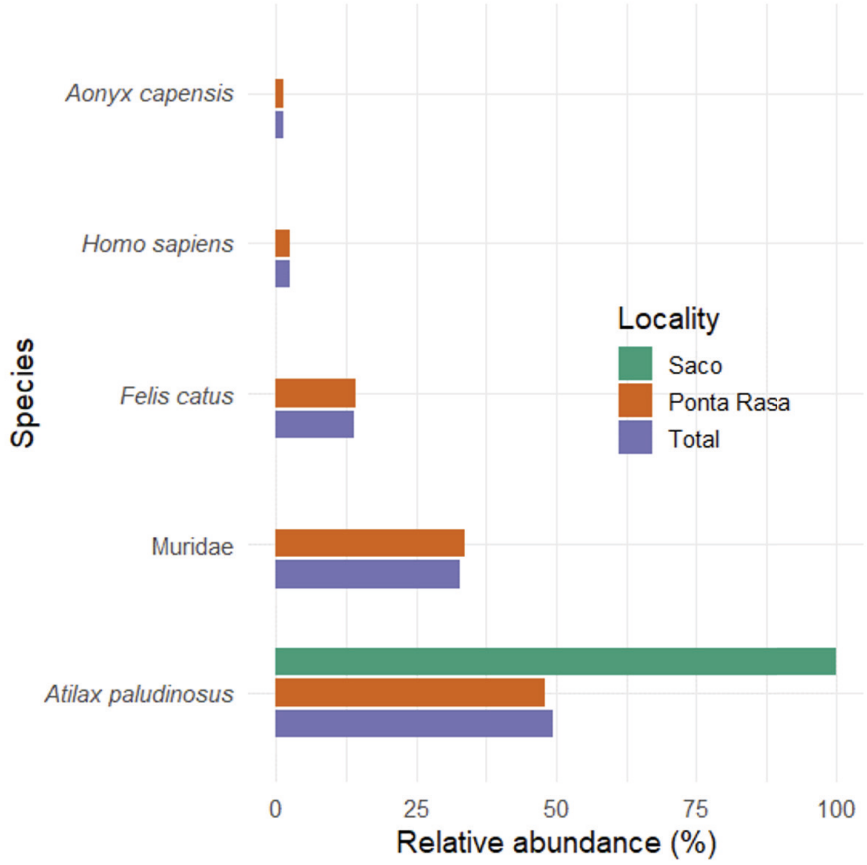

Figure 5. Relative abundance (%) of mammal species detected through camera trapping or tracks in the mangroves of Inhaca Island, and the overall total. The Noge mangrove is omitted, as no mammal activity was recorded there.

differences among the mangrove systems, site-specific tidal regimes, and the behavioral ecology of the species most frequently detected in Ponta Rasa may also have influenced the observed distribution patterns. Moreover, resource availability likely plays a critical role in shaping species occurrence and activity. Globally, a positive correlation has been observed between terrestrial vertebrate alpha diversity and mangrove tree richness across both recorded and potential distributions (Rog et al., 2017). Consequently, due to its smaller size, Ponta Rasa likely harbors a greater diversity of tree species, including

both mangroves and those in the surrounding forested habitat, providing microhabitats that support mammals that rely on them for food.

The comparison of species-specific relative abundance across the three study sites further underscores a pronounced spatial disparity in detection frequencies. *Atilax paludinosus* was the only species recorded on more than one site (Ponta Rasa and Saco). All other species were exclusively recorded in Ponta Rasa, each accounting for 100% of their respective detection frequencies. No mammalian species were detected at the Noge site during the sampling period, suggesting either a true absence or extremely low detection probabilities. These patterns were corroborated by statistical analysis.

Taken together, the findings suggest that Ponta Rasa supports higher mammalian activity or detectability, likely due to favorable habitat conditions, greater resource availability, and potentially more effective sampling coverage. This highlights Ponta Rasa as a key area for terrestrial mammal conservation on Inhaca Island and underlines its potential importance for maintaining functional diversity.

We note that this study was conducted as an educational exercise aimed at fostering student self-learning. As such, the results presented here are preliminary. Future research should ensure standardized sampling efforts across sites and incorporate metrics such as the Relative Abundance Index (RAI), based on photographic evidence and track surveys conducted systematically across all mangrove areas.

V. Limitations

We calculated relative abundance; however, we recommend using the Relative Abundance Index (RAI) to standardize sampling effort and generate more robust results, enabling rigorous application of statistical tests and diversity indices.

VI. Recommendation

Due to the low number of records obtained per mangrove site, we advise deploying camera traps for a longer duration at each location. We learned that developing a well-structured dataset is essential to enable reliable comparisons of species richness and to standardize sampling efforts with the Relative Abundance Index (RAI), thus avoiding potential bias in the results. Such a dataset would allow for more robust analyses. We recommend that students participating in future summer schools pay special attention to this aspect.

VII. Conclusions

We observed a marked disparity in mammalian diversity and detection across the mangrove sites, underscoring the critical conservation value of Ponta Rasa on Inhaca Island. This is further supported by the presence of *Atilax paludinosus*, which relies on riverine vegetation for shelter; the loss of this habitat may lead to localized population declines in areas experiencing degradation (Do Linh San et al., 2015). Additionally, the presence of the otter *Aonyx capensis* reinforces the importance of conserving the Ponta Rasa mangrove, as this species is classified as Near Threatened by the IUCN (Jacques et al., 2021).

The species richness and activity at this site likely reflect a combination of lower anthropogenic disturbance, favorable habitat structure, and resource availability. Conversely, we noted the absence of detections at Noge, highlighting potential ecological degradation or limited detectability that warrants further investigation. Although our findings are preliminary, stemming from a student-led exploratory study, they provide a foundational basis for future research. We recommend that subsequent studies employ standardized sampling protocols and incorporate quantitative abundance indices, such as the Relative Abundance Index (RAI). Ultimately, focused conservation strategies at priority sites like Ponta Rasa are crucial to ensuring the long-term survival of both species.

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*A pair of marsh mongooses (*Atilax paludinosus*, Herpestidae), captured in a trap-camera photo, patrols the mangrove edge at Ponta Rasa. The most common medium-sized mammals on the island, they hunt crabs and other marine fauna and defecate in latrines on terra firme promontories, thereby contributing to the exchange of nutrients between the sea and land.*

DIVERSITY AND ABUNDANCE OF ZOOPLANKTON AND FISH LARVAE IN MANGROVE ECOSYSTEMS IN INHACA ISLAND

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Abstract: Mangrove ecosystems play a crucial role as nursery habitats for marine species, where zooplankton support the early life stages of fish through key trophic interactions. In this study, we investigated the diversity and abundance of zooplankton and fish larvae in the mangrove ecosystems of Inhaca Island, Mozambique. We collected samples from mangrove channels (Saco and Noge), their entrance (Saco Bay), and a nearby coral reef (Santa Maria coral reef) using plankton nets with 90 µm and 500 µm mesh sizes. At each site, we recorded environmental parameters such as temperature, salinity, and depth. We identified and quantified zooplankton taxa and assessed their densities across sites. We found the highest zooplankton abundance and diversity at the coral reef site (896 ind/m^3), primarily composed of copepods and decapods. The highest fish larvae density occurred at the entrance of the mangrove channels (31 ind/m^3). In contrast, zooplankton and fish larvae were less abundant within the mangrove channels, likely due to strong tidal flushing and predation pressure. Despite the lower densities, we observed high taxonomic diversity, including various genera of copepods and decapods. Our findings underscore the ecological importance of these coastal systems and highlight the need for continued monitoring to support their conservation and sustainable management.

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Keywords: Zooplankton diversity, Fish larvae, Mangrove ecosystems, Inhaca Island, Coastal biodiversity.

I. Introduction

Mangroves, a group of plants that inhabit the intertidal zone along tropical and subtropical coastal areas, provide habitat, shelter, food, and breeding grounds for a diverse array of organisms (Kibirige et al., 2006; Nagelkerken et al., 2008; A. I. Robertson & Duke, 1987). Various fish, mollusk, and crustacean species inhabit these habitats, completing their entire life cycle or part of it in mangrove channels or creeks. Many larval and juvenile stages of these organisms rely on zooplankton as their food (Campos et al., 2022; Ooi & Chong, 2011). Consequently, zooplankton, microscopic floating organisms that drift with water currents, form an integral component of mangrove food webs, significantly contributing to biological productivity and playing a crucial role in energy transfer (Chew et al., 2012; Vu et al., 2017). However, we know little about the diversity and abundance of zooplankton in mangrove channels compared to open ocean habitats.

The abundance, diversity, and distribution of zooplankton provide information about the ecological conditions and quality of habitats (Ndah et al., 2022). Various environmental factors interact to create beneficial spatial and seasonal conditions for zooplankton growth (Abdul et al., 2016; Balqis et al., 2016). Bottom-up and top-down processes largely affect the diversity and abundance of zooplankton, which serve as bioindicators to monitor aquatic ecosystems and water integrity (Bednarski & Morales-Ramírez, 2004; Sanvicente-Añorve et al., 2022). Factors such as the nutritional status of the water body, the availability of phytoplankton, abiotic variables like oxygen concentration or water-column mixing, and predation pressure by zooplankton-feeding organisms influence their distribution, diversity, and abundance (Ahmad et al., 2011). Zooplankton also regulate algal and microbial productivity through predation, facilitating the transfer of primary productivity to fish and other consumers (Ersoy et al., 2019; Zuo et al., 2015).

The early life stages of fish, including the egg and larval stages, are part of the plankton, termed ichthyoplankton, due to their low

swimming mobility (Allen & Horn, 2006). Many fish species use mangrove habitats as spawning grounds and nursery areas, and the survival of fish larvae heavily relies on environmental conditions and the availability of zooplankton, their primary prey (Tarimo, 2022).

Published data on zooplankton in coastal mangrove ecosystems on Inhaca Island are scarce, with available studies mainly restricted to specific aspects of some taxonomic groups, such as phytoplankton and foraminifera (Braga, 1960; e Silva, 1960; Paula et al., 1998; Pinto, 1996). Therefore, studying the zooplankton in mangrove channels on Inhaca Island is important to understand its diversity and ecological role in the food web. This will help monitor the overall quality of the ecosystem, detecting possible environmental changes resulting from pollution or climate variations. Quantification allows assessment of the ecosystem's productivity and its capacity to support fish populations and other marine organisms. These data are essential for the conservation and sustainable management of marine resources in the region.

Here, we assessed the diversity and abundance of zooplankton in the mangrove ecosystems of Inhaca Island. We identified and quantified the dominant zooplankton taxa in mangrove channels at high tide and the entrance of the mangrove channels and compared this to a nearby coral reef to evaluate the overall zooplankton diversity and productivity in this area.

II. Methods

A. *Study area*

We conducted the study on Inhaca Island, located approximately 32 km east of Maputo, the capital of Mozambique, at 26°S latitude and 33°E longitude, with an area of about 40 km² (Moreira, 2005). We selected three sampling sites on the island: mangrove channels (Saco and Noge village), outside mangrove channels (Saco Bay), and one coral reef area (Santa Maria coral reef) (Figure 1).

Noge is a channel surrounded by a mangrove forest composed mainly of *Ceriops tagal*, *Rhizophora mucronata*, and *Xylocarpus granatum*. Saco,

Figure 1. Location of the study area. *Left*: Inhaca Island, showing sampling sites from north to south: (a) the channel at Noge mangroves; (b) the channel at Saco Bay; (c) Saco Bay; and (d) Santa Maria coral reef. *Lower right*: Location of Inhaca Island (white arrow) within Maputo Bay, southern Mozambique. *Upper right*: Location of Mozambique on the African continent. Projection: Universal Transverse Mercator Zone 36S. Datum: WGS 1984. Data source: CENACARTA.

located in the southern part of Inhaca Island, is a small, semi-enclosed bay that includes a channel with a total area of 60 ha. Mangrove forests, dominated by three species, *R. mucronata*, Avicennia marina, and *C. tagal*, cover the area. The entrance of the Saco mangrove channels is characterized by relatively shallow waters. The coral reef in the Santa Maria coral reef area currently exhibits a low density of corals, at least partially attributable to turbidity and sand movement caused by the tidal flush that fills and drains the Saco mangrove and bay (Schleyer & Pereira, 2014).

B. *Sample collection*

We collected ichthyo- and zooplankton samples at each site during high or intermediate (Noge) tide between 15 and 19 October 2024. We employed two 40 cm diameter plankton nets: one with a 90 µm

Figure 2. Selected activities conducted during the project. *Left*: Plankton sample collection in the field. *Center*: In situ salinity measurement. *Right*: Microscopic analysis of collected samples.

mesh for zooplankton and another with a 500 µm mesh for fish larvae, each fitted with a flowmeter to determine volume. We towed the nets horizontally below the surface, or deeper when feasible, for two to five minutes using a motorized boat, except at Noge, where we used a rowing boat. In each mangrove channel site, we took three replicate samples to span the entire length of the channels. Outside the mangrove and at the coral reef, we collected two and three samples, respectively, expecting a more uniform distribution in open water. We preserved the samples in ethanol and examined them using a stereomicroscope. We also recorded temperature, salinity, and water depth at each sampling event.

We examined the entire volume of all plankton samples from both the 90 µm and 500 µm mesh nets for fish larvae. For zooplankton identification and abundance estimation, we used subsamples from the 90 µm mesh net, counting up to 100 individuals of copepod taxa. We identified zooplankton to higher taxonomic levels or, where possible, to genus level, following Conway et al. (2003) and Larink & Westheide (2011). We also used Leis & Carson-Ewart (2021) in the case of the fish.

We estimated the density of taxa per volume of water filtered by dividing the number of organisms by the filtered volume. We calculated the filtered volume by multiplying the area of the net by the distance recorded by the flowmeter.

III. Results

A. *Environmental conditions of sampling site*

We measured an average water temperature of 23.72 °C and a salinity of 40.63 g/L in the mangrove channels across all three sites, with depths ranging from two to four meters. In the open water outside the mangrove channels, we recorded an average water temperature of 22.75 °C, a salinity of 40 g/L, and depths between three and 10 meters. At Santa Maria coral reef, we found an average water temperature of 24.70 °C, a salinity of 40 g/L, and a depth of approximately four m (Figure 3).

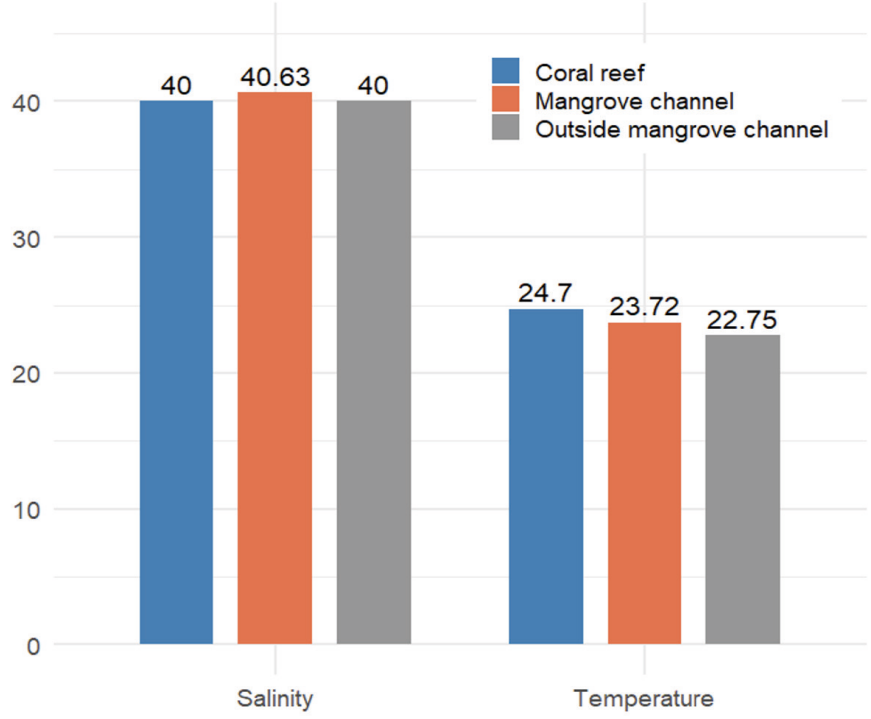

Figure 3. Mean temperature (°C) and salinity recorded in three different habitats of the Inhaca Island: mangrove channel, outside the mangrove channel, and coral reef.

B. *Zooplankton abundance*

We observed varying densities of different taxa across all four sites, with copepods and decapods emerging as the most abundant taxa, reaching densities up to 762.42 ind/m^3 and 125.13 ind/m^3, respectively (Table I). The coral reef sampling site at Santa Maria coral reef proved the most productive, boasting a total density of 896.44 ind/m^3 and hosting all identified taxa considered in this study. We recorded the highest density of fish larvae at the entrance of the mangrove channel in Saco Bay, reaching 31.37 ind/m^3, while fish egg density peaked in the Santa Maria area at 18.88 ind/m^3.

Table 1. Density (ind/m3) per taxa at the four different sampling sites of Inhaca Island.

Taxa	**Saco-Mang.**	**Noge-Mang.**	**Saco-Bay**	**Santa Maria**
Cephalopoda	0.00	0.00	0.00	0.28
Chaetognatha	0.00	0.00	11.79	8.42
Cirripedia	0.06	0.00	0.00	1.11
Cladocera	0.00	0.00	0.00	0.56
Copepoda	12.72	18.38	327.81	762.42
Decapoda	1.68	4.53	125.13	69.62
Echinoderma-ta	0.18	0.00	7.60	0.28
Fish egg	0.26	0.10	3.80	15.88
Fish larvae	0.03	0.00	31.37	3.09
Gastropoda	0.00	0.10	0.00	24.98
Polychaetha	0.44	0.00	0.00	1.39
Pterapoda	0.35	0.00	11.40	2.81
Radiolaria	0.00	0.00	0.00	5.61
Total	23.11	518.90	15.73	896.45

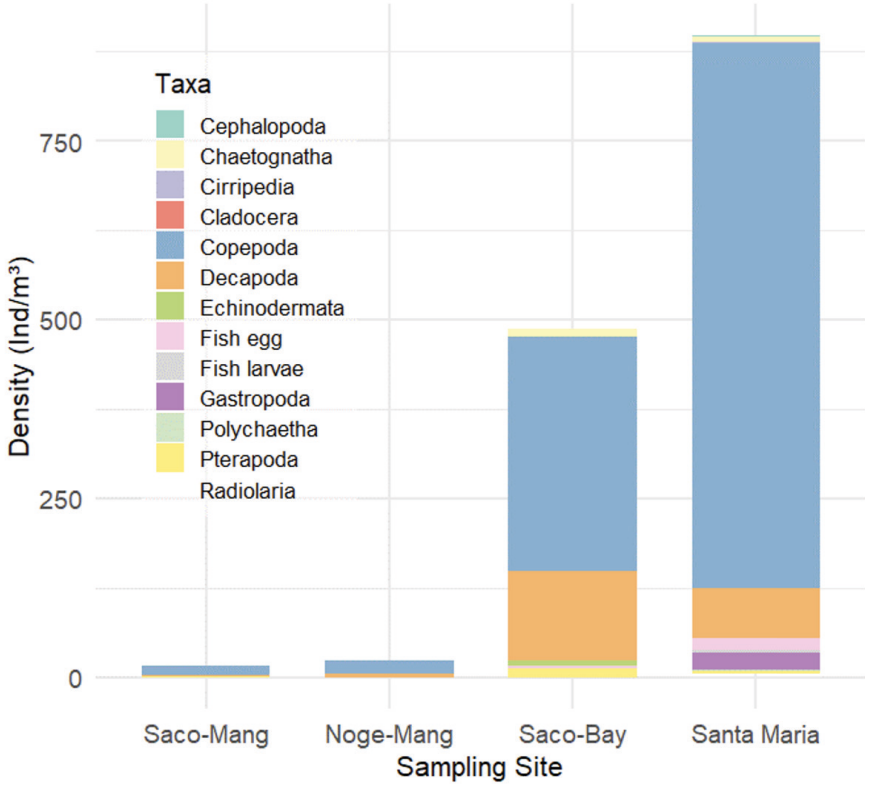

Figure 4. Density (Individual/m3) per taxonomic group across the four different sampling sites.

C. *Zooplankton diversity*

We documented a high diversity of copepods in the samples, including Calanoida, Cyclopoida, and Harpacticoida. Figure 5 illustrates examples of the variety of copepods we analyzed in the samples.

We found Decapoda to be highly diverse, encompassing familiar crabs, prawns, and shrimps (Conway et al., 2003). We observed various life stages of decapods, including nauplius, zoea, and adult stages, with particularly high numbers of Luciferidae (Figure 6).

We observed a high abundance of Pteropoda, small-sized planktonic gastropods with lobed feet forming two lateral fins, Polychaeta (Larink & Westheide, 2011) (Figure 7), and fish larvae in the samples (Figure 8).

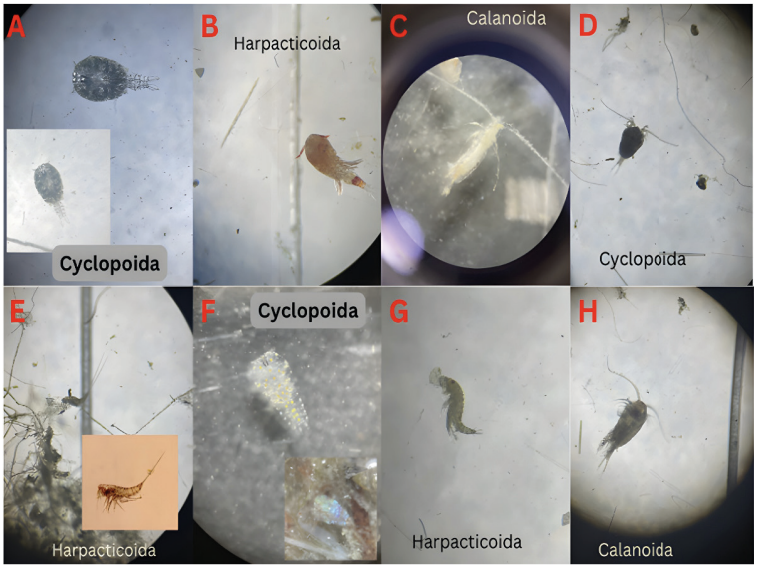

Figure 5. Diversity of Copepods A) Cyclopoida, *Vettoria* sp.; B) Harpacticoida; C) Calanoida, *Rhinocalanus* sp.; D) Cyclopoida; E) Harpacticoida, *Microsetella* sp.; F) Cyclopoida, *Sapphirina* sp.; G) Harpacticoida, *Euterpina* sp.; H) Calanoida, *Temora* sp.

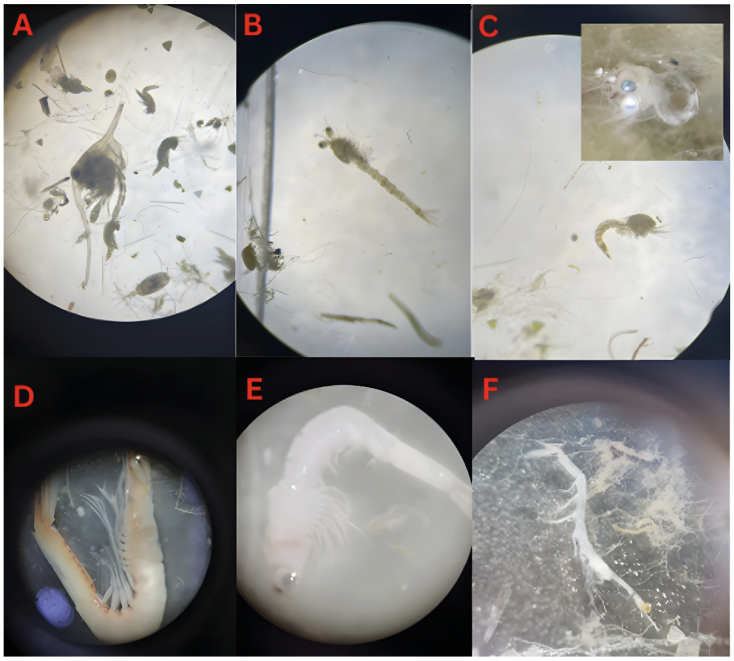

Figure 6. Diversity of Decapoda. (A-C) Zoea larvae; (D-E) Juvenile stage; F) *Lucifer* sp.

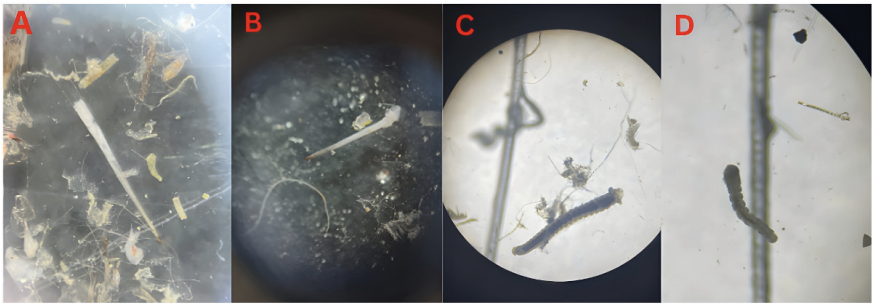

Figure 7. Miscellaneous organisms found in the zooplankton samples. (A-B) Pteropoda; (C-D) Polychaeta.

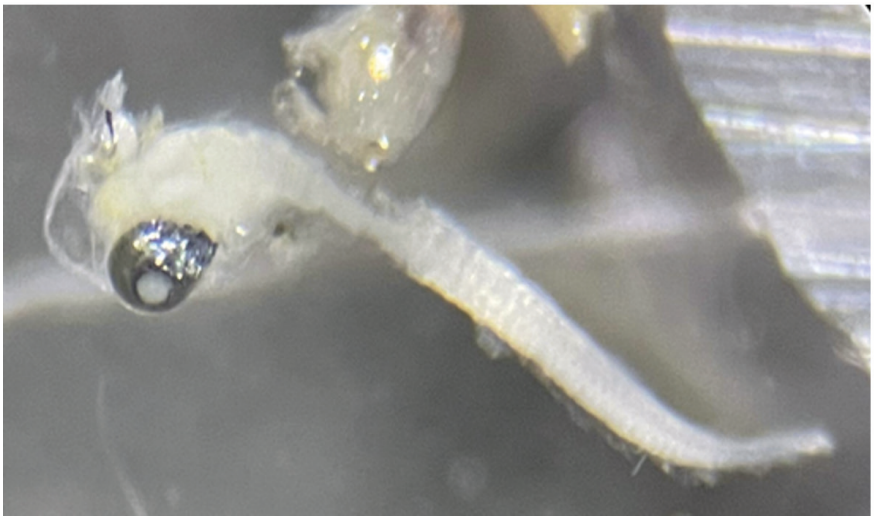

Figure 8. Fish larvae.

IV. Discussion

A. *Zooplankton in mangrove channels*

We found relatively low zooplankton abundances in the channels of the Inhaca mangrove, contrasting with the trend observed in other mangrove habitats, which are typically rich in zooplankton due to their role as shelter, food sources, and breeding grounds for these species (Ramdonee & Appadoo, 2015; A. Robertson & Blaber, 1992). An

earlier study confirms low abundances in mangrove channels, noting similar densities over the season, except for a brief peak at one sampling location in September (Paula et al., 1998). We suggest that the low abundances of zooplankton and fish larvae in our study may be attributed to seasonality, strong tidal flushing, and high predation pressure on zooplankton in mangrove channels.

Previous studies in mangrove channels reveal high seasonal variation in zooplankton density. For instance, Paula et al. (1998a) observed that penaeid larval stages peak in abundance in May, primarily in the Saco mangrove area. We note that tidal flushing strongly affects zooplankton abundance. During low tide, dropping water levels in the channels expose zooplankton to predators and reduce their available habitat. At high tide, larger zooplankton can flush out of the channels, further decreasing their abundance (Srichandan et al., 2021; Trinast, 1975). We also recognize that flushing dynamics contribute, as currents in the mangrove channels can carry larger zooplankton out to open water, further reducing their local abundance.

We identified high predation pressure in mangrove channels, which typically host large numbers of fish, as an additional factor contributing to low zooplankton abundance. We observed a low number or absence of larger-sized zooplankton in samples from the larger mesh size (500 µm) net compared to those from the smaller mesh size (90 µm) net in both mangrove channels. Predation significantly affects larger zooplankton, which are particularly vulnerable to fish and crustacean predators, impacting their population abundance (A. Robertson et al., 1988; Tarimo, 2022). Together, these factors explain the low abundance of larger zooplankton in the mangrove channels of Saco de Inhaca.

We found that Copepoda and Decapoda comprised the taxa with the highest abundances. Copepoda generally dominate marine zooplankton systems, exhibiting high diversity, particularly in the tropical and subtropical Indian Ocean, with up to 993 species (Razouls et al., 2005). We observed a wide size range of copepod species, from smaller ones like *Microsetella* (<1 mm) to larger ones like *Rhincalanus* (up to 3 mm or more in length). Similarly, we noted that Decapoda form a diverse group, including familiar crabs, shrimps, and prawns, as well as

taxa that remain planktonic throughout their entire life cycle or during early life stages.

We recorded the highest abundances of zooplankton and fish larvae at the open ocean site of Santa Maria coral reef, reaching values up to 896.44 ind/m^3. The relatively high turbidity of the water column during sampling, combined with abundant phytoplankton collected in the nets, indicates robust plankton production, driven by high primary productivity in this area and upwelling within the Agulhas Current (Mann & Lazier, 2006).

Zooplankton organisms are an important intermediary link by transferring carbon and essential nutrients from primary producers (phytoplankton) to fish, birds and mammals. This was particularly evident with the presence of flamingos in and around the mangrove channels, their pink coloration derived from carotenoid pigments produced by the plankton community (Fox, 1955).

We emphasize that monitoring the zooplankton community in Inhaca will serve as a vital indicator of overall water quality and support for the production of abundant fish, bird, and mammal life.

V. Conclusions

We observed high taxa diversity and abundance in the open water sites outside the mangrove channels. Our group identified several abundant taxa, including Cephalopoda, Chaetognatha, Cirripedia, Cladocera, Copepoda, Decapoda, Echinodermata, Gastropoda, Polychaeta, Pteropoda, and diverse fish eggs. We found that copepods and decapods were the most abundant taxa, reaching densities of up to 762.42 ind/m^3 and 125.13 ind/m^3, respectively. We recorded the highest density of fish larvae in Saco Bay at 31.37 ind/m^3, while fish egg density peaked at Santa Maria coral reef at 18.88 ind/m^3. The coral reef area at Santa Maria proved the most productive sampling site, with a total density of 896.44 ind/m^3 and the presence of all highlighted taxa considered in our study. We emphasize the importance of preserving this rich biodiversity to sustain the biological production of marine life.

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A traditional boat and its crew off the coast of Inhaca highlight the vital human connection to mangroves, which anchor the oceanic trophic pyramid as essential nurseries, offering safe refuges and oviposition grounds for early-stage marine species that fuel the entire ecosystem. These mangroves not only sustain ecological balance but also drive the local economy by supporting abundant fish populations critical to the livelihoods of fishing communities and the broader coastal market. (photo by Paolo Ramoni-Perazzi).

ACOUSTIC INVESTIGATION OF BIRD SPECIES DIVERSITY IN MANGROVE FORESTS

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Abstract: Mangrove ecosystems, which are critical habitats for diverse bird species, are facing global declines, necessitating the development of effective monitoring strategies. This study employed bioacoustic monitoring to assess avifauna diversity in the Saco da Inhaca mangrove forest, Mozambique, over a three-day survey in October 2024. Using mobile phone recordings and Audacity software, we identified 27 bird species across 17 families, with Pycnonotidae (bulbuls) and Nectariniidae (sunbirds) being notably abundant. Species accumulation curves indicated incomplete sampling, suggesting higher potential diversity. Statistical analyses (GLM and GAMM) revealed weak correlations between sampling effort, time of day, and species richness, with spatial autocorrelation indicating the presence of unmodeled environmental factors, such as microhabitat structure. Bioacoustic methods, supplemented by tools like BirdNET and xeno-canto, proved effective for non-invasive monitoring in dense mangroves, despite limitations from short survey duration and equipment constraints. These findings provide baseline data for conservation, highlighting the ecological roles of birds in nutrient cycling and seed dispersal, and underscoring the need for extended monitoring to capture seasonal and cryptic species in this biodiverse ecosystem.

Keywords: Bioacoustics, Mangroves, Avifauna diversity, Saco da Inhaca, Conservation.

I. Introduction

Mangroves, which occur in tropical and subtropical coastal intertidal zones, provide critical habitats for numerous bird species, supporting

their feeding, roosting, and nesting activities (Mestre et al., 2007; Nagelkerken et al., 2008). These resource-rich ecosystems underpin biodiversity and ecological processes in coastal regions (Romañach et al., 2018; Tomlinson, 1994), including bird communities, which in mangroves can be species-rich relative to their low floristic diversity (Buelow & Sheaves, 2015).

However, global mangrove cover has declined by over 50% due to coastal development, aquaculture, and land conversion, threatening associated fauna (Alongi, 2002; Spalding et al., 2010): a particularly sensitive issue in Mozambique, given its extensive mangrove surface spanning more than 300,000 hectares (Shapiro, 2018), and the limited ornithological information available (Trezza et al., 2023).

As with other natural ecosystems, the conservation status of mangroves can be assessed directly through the evaluation of various physical and chemical parameters, or indirectly through the evaluation of indicator species, particularly avifauna, due to their sensitivity to environmental changes (Luther & Greenberg, 2009; Padmakumar & Joseph, 2022). Moreover, birds play a vital role in mangrove ecosystems, including contributing to nutrient cycling through foraging and fecal deposition (Appoo et al., 2024; Lovelock et al., 2004).

For instance, avifauna diversity studies are crucial for establishing baseline data, assessing habitat degradation, and informing conservation strategies for coastal ecosystems (Poonam & Kurve, 2017; Tamekloe et al., 2025). In this regard, bioacoustic monitoring provides a non-invasive and effective method in dense habitats, allowing standardized and scalable data collection with reduced observer bias in visually inaccessible environments, while also enabling bird species identification, diversity quantification, and assessment of habitat use patterns (Marques et al., 2013). Therefore, bioacoustics constitutes an interesting tool for conservation in biodiverse regions such as Mozambique, particularly in its mangroves.

We employed bioacoustic monitoring to investigate avifauna diversity and habitat use in the Saco da Inhaca mangrove, Mozambique. We recorded bird vocalizations to identify species and assess their diversity, distribution, and ecological roles non-invasively, contributing to baseline data for conservation management in this vital mangrove ecosystem.

II. Objectives

A. *General*

Evaluate and document the diversity of bird species present in the mangrove forests of Saco da Inhaca through acoustic surveys.

B. *Specific*

- Identify the most common species in the mangrove forests of Saco da Inhaca.
- Analyze the acoustic characteristics of bird calls and songs to assess species abundance.
- Examine the distribution of species in relation to environmental conditions and vegetation types in Saco.

III. Methodology

A. *Study area*

Our study focused on a portion of the Saco mangrove forest, located in the southern part of Inhaca Island. The island lies approximately 32 km east of Maputo, within Maputo Bay (25°58'S–26°04'S; 32°53'E–32°59'E). Covering 42 km², Inhaca Island has a transitional climate between tropical and warm subtropical, with hot, rainy summers (November–April) and cooler, dry winters (May–October) (de Boer et al., 2000; Kalk, 1996). The region experiences semi-diurnal tides, with a maximum spring tidal range of 3.9 m (Boer & Longamane, 1996).

The Saco is a bay in the southern part of Inhaca Island, bordered for most of its extent by mangrove forest. Our fieldwork focused on an approximately 40 ha triangular portion of these mangroves (Figure 1), bounded by heavily anthropized vegetation on the southwestern and southeastern sides, and by the Saco lagoon on the northern side. This area is traversed by a natural channel that narrows as it approaches higher elevations. It represents one of the most pristine and densely

vegetated mangroves stands on the island, dominated by five species: *Avicennia marina, Rhizophora mucronata, Ceriops tagal, Bruguiera gymnorrhiza,* and *Lumnitzera racemosa* (Boer & Longamane, 1996).

B. *Field survey and data collection*

From October 16, 2024, we conducted a three-day qualitative survey combining direct observations and vocalization recordings at randomly selected sampling points during morning hours from 08:30 to 12:30. We recorded the soundscape using mobile phones, with 5-minute recording intervals at each point, repeated every 30 minutes, for three to four cycles per session. All five authors stationed approximately 250 meters apart, collected data simultaneously across multiple points. We also documented visual observations using binoculars.

C. *Data analysis and identification*

We used Audacity software (Audacity Team, 2024) to generate spectrograms of the soundscapes, from which we detected bird vocalizations and manually selected segments to create a bird song library for different species. We chose these clips based on minimal environmental noise, vocalization clarity, and uniqueness. To identify birds, we consulted field guides, including Sinclair & Hockey (2020), and collaborated with local ornithologists. For bird vocalizations, we compared selected clips with recordings available on xeno-canto, an online database of shared bird sounds contributed by a global community (Xeno-canto Foundation, 2024). We uploaded all identified recordings to this platform in a curated list. Additionally, we evaluated the performance of BirdNET v1.0 (Kahl et al., 2021), a machine-learning application, to assist in species identification, accounting for misclassifications to assess its accuracy. This process enabled us to compile a comprehensive library of bird songs, categorized by species, which serves as a valuable resource for future bioacoustic studies, with taxonomy confirmed using (Clements et al., 2022).

We used R language (R Core Team, 2023) to conduct further statistical analyses. We generated Species Accumulation Curves to assess

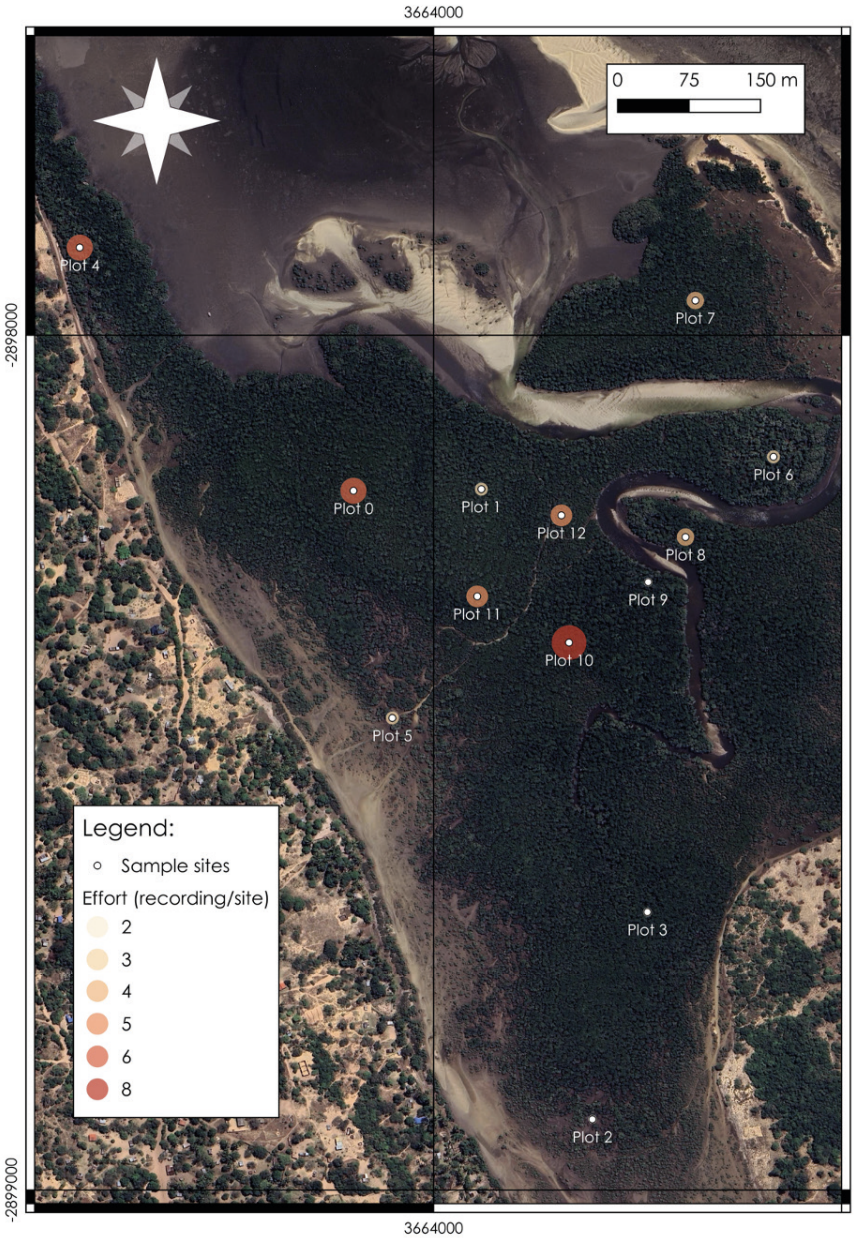

Figure 1. Map of sampling plots in Saco Bay. Points are shown in a color gradient proportional to recording effort, with darker shades indicating higher numbers of recordings and lighter shades fewer recordings.

species inventory completeness in the Saco da Inhaca mangrove forest. We applied a Generalized Linear Model (GLM) and a Generalized Additive Mixed Model (GAMM), both with a Poisson distribution, to account for various explanatory variables. We also conducted a Moran's I Test to assess spatial autocorrelation.

IV. Results

We discovered pronounced differences in bird species diversity across sites in the Saco da Inhaca mangrove forest, driven by habitat variability and proximity to human settlements. The species accumulation curve underscored the effectiveness of our mixed approach, revealing a remarkable number of species detected in a brief period, despite most team members' limited familiarity with local avifauna. As the curve did not reach a plateau, further sampling is necessary to document the local bird community fully.

A. *Diversity of avifauna in Saco da Inhaca*

Our preliminary survey revealed a weak positive relationship between sampling effort and species richness ($r = 0.29$), indicating that sampling sessions accounted for approximately 9% of the observed variation in richness across plots (Figure 2). No spatial pattern was detected, as plots with higher-than-expected diversity (plots 7 and 9) were located near those with lower-than-expected species richness (plots 1 and 6) within the Saco da Inhaca mangrove forest (Figure 3). This suggests that additional factors, such as specific habitat structure, microhabitat availability, or species detectability, likely exert a stronger influence on observed richness than sampling intensity, or proximity to the mangrove border or channel alone.

We identified 27 bird species across 17 families and 10 orders (Appendix A), offering a snapshot of avifauna diversity in this vital ecosystem. The Pycnonotidae (bulbuls) family stood out, with 24 individuals recorded, making it the most frequently recorded family. The Nectariniidae (sunbirds) family notably contributed to diversity, with

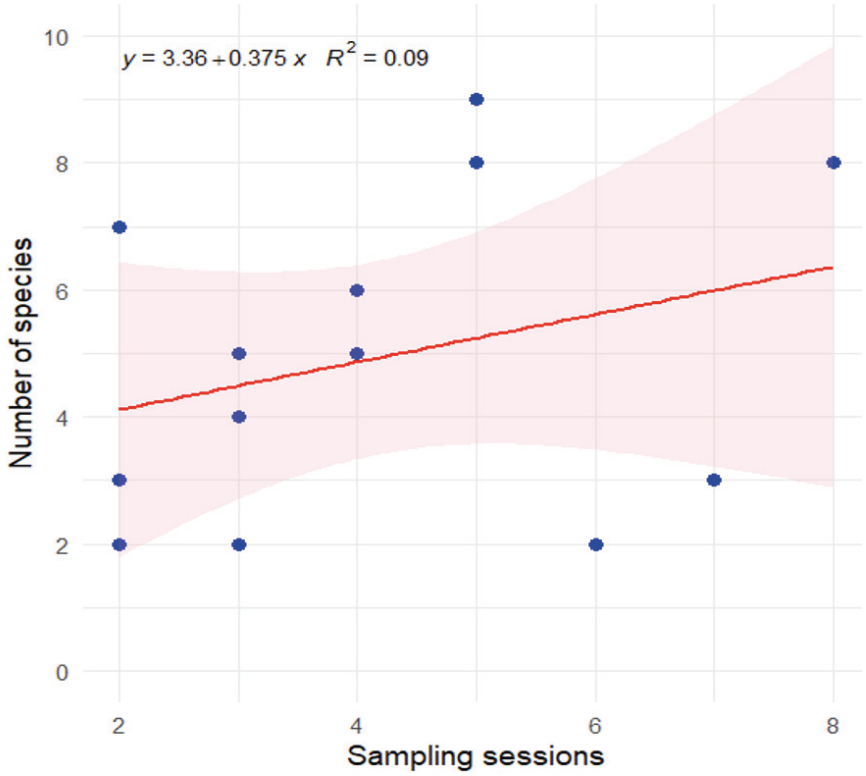

Figure 2. Relationship between the number of sampling sessions and recorded bird species richness across 13 plots in the mangrove of Saco de Inhaca. Points represent individual plots, the red line indicates the fitted linear regression, and the shaded area shows the 95% confidence interval.

five individuals observed. The Scolopacidae (sandpipers) and Laridae (gulls) families also showed significant abundance, each with five individuals recorded. Other families, including Fringillidae (finches) with one individual, Cisticolidae (cisticolas) with one to two individuals, and Threskiornithidae (ibises) with one individual, exhibited lower counts, underscoring the varied distribution of avifauna in this habitat.

B. *Performance of data collection*

The Species Accumulation Curve (SAC) indicated that our survey did not fully capture the total bird diversity of Inhaca Island, as the curve

failed to reach a plateau (Figure 4). The Generalized Linear Model (GLM) indicated deviance residuals near zero and a Nagelkerke R^2 of 1.000, which suggest a nearly perfect fit to the observed data. However, such results are atypical for ecological count data and likely reflect overfitting or model specification issues rather than true explanatory power. None of the predictors showed a statistically significant effect at the conventional 0.05 threshold. The variable *time of day* (p = 1.000) and *effort* (p = 0.498) had no detectable influence on species richness. Plot-specific effects varied in direction, with Plot 10 (p = 0.043) and Plot 4 (p = 0.065) showing marginal associations, though these should be interpreted with caution given the instability of the model and wide confidence intervals. Overall, while the model fits the observed data almost exactly, the results are more consistent with overfitting than with robust ecological signal detection.

The Generalized Additive Mixed Model (GAMM) explained very little variation in species richness (R^2 = 0.015). The smooth term for hour of day had an effective degree of freedom (EDF) of 1.000 and was not significant (p = 0.906), indicating no temporal effect on species counts. The smooth term for plot number (EDF = 0.648, p = 0.093) suggested weak variability across plots but without strong statistical support. Moran's I statistic for the GAMM residuals was 0.591 (p < 0.001), with the scatterplot showing a positive slope between residuals and their spatial lags (Figure 5). This indicates strong positive spatial autocorrelation: sites with higher (or lower) residuals tend to be located near sites with similarly high (or low) residuals. Such clustering suggests that the model does not adequately capture spatial dependence, and that unmodeled spatial structure remains in the data.

V. Discussion

The acoustic survey in the Saco da Inhaca mangrove forest, combining direct observations and bioacoustic recordings, proved a convenient and efficient methodology for conducting avifauna inventories in a short time (three days), enabling team members with limited familiarity with local bird species to detect 27 species despite minimal

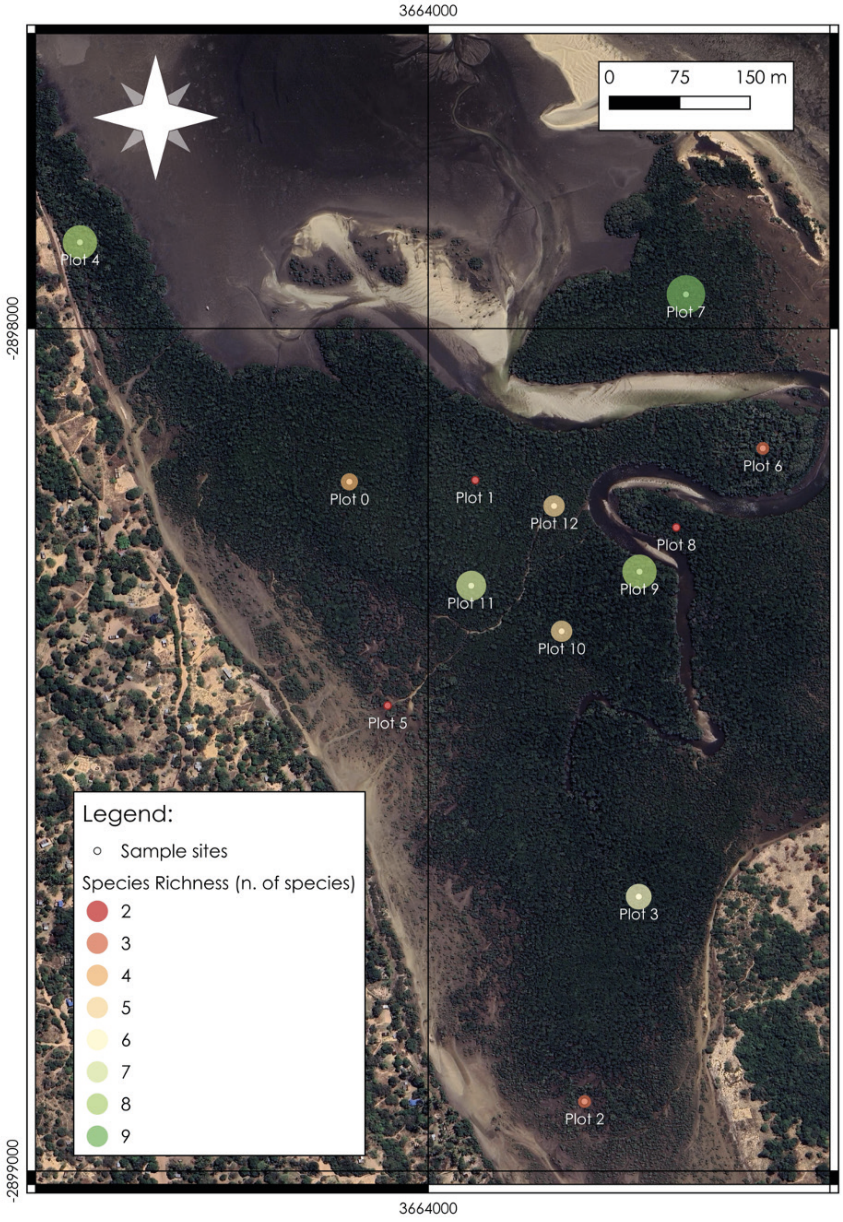

Figure 3. Map of species richness in Saco da Inhaca mangrove forest. Points are marked with a color gradient: larger, greener points indicate higher species richness; smaller, reddish points denote fewer species recorded.

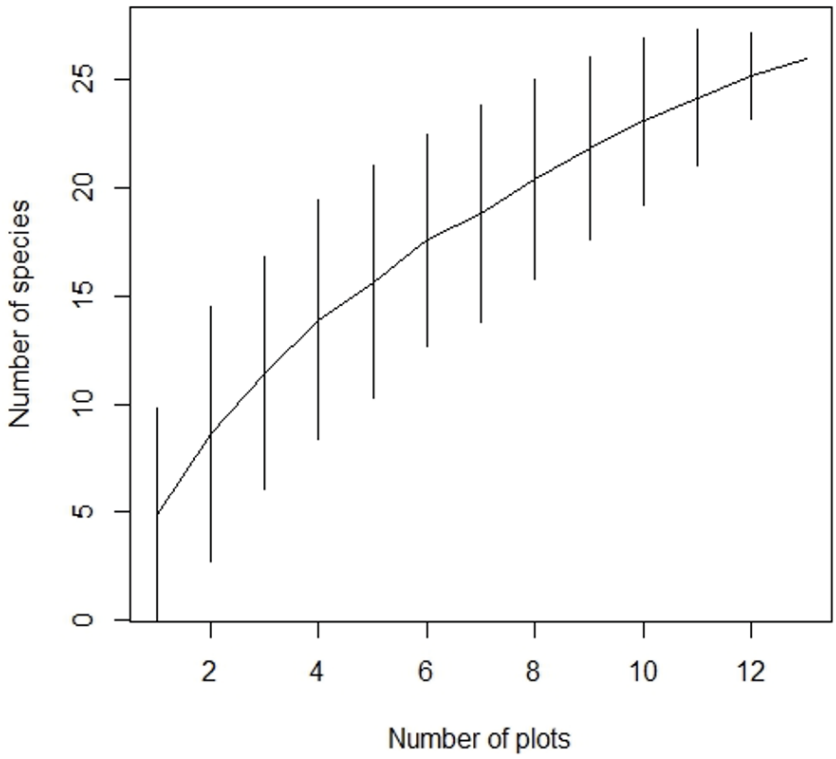

Figure 4. Species accumulation curve of birds across sampled plots in the Saco da Inhaca mangrove forest. The curve displays the cumulative number of species recorded with increasing sampling effort (plots), with error bars indicating standard deviations from random permutations.

prior knowledge. In comparison, the eBird hotspot for "Inhaca Island" (https://ebird.org/hotspot/L4578165/bird-list) lists a total of 205 bird species recorded since the earliest checklists, by some 26 observers (typically well-trained), in 48 checklists, often involving extensive searches over large distances and hours of effort, yielding an average of approximately 24 species per checklist. The Saco da Inhaca mangrove is relatively narrow and embedded in a mosaic of other vegetation types, making it reasonable to expect detections of species more typical of terrestrial environments. However, the predominance of terrestrial groups such as bulbuls (Pycnonotidae) and sunbirds (Nectariniidae) highlights

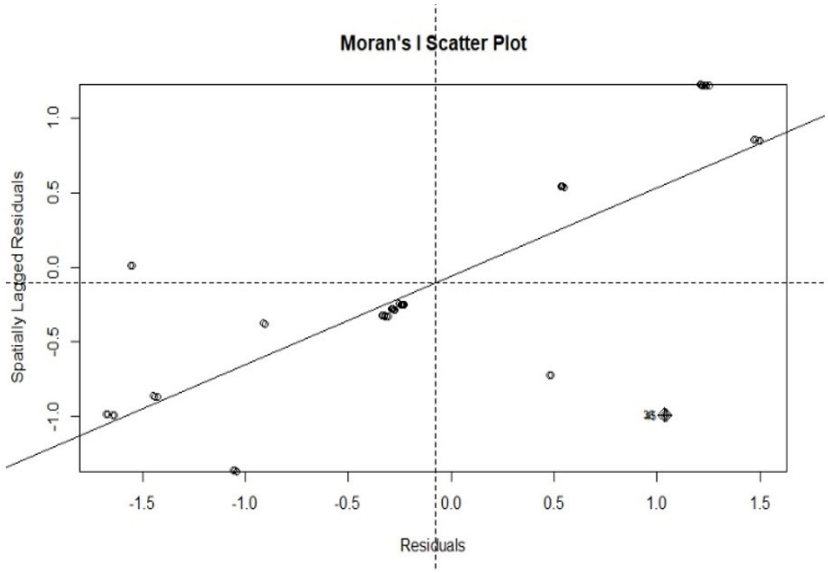

Figure 5. Moran's I scatterplot for the GAMM residuals. The x-axis shows the residual values, and the y-axis represents their spatially lagged counterparts. The solid line indicates the slope used to calculate Moran's I.

the importance of mangroves as integral elements for these groups and their interconnection with surrounding vegetation mosaics. The poor detection of otherwise abundant groups like Threskiornithidae (ibises) points to limitations of the bioacoustic approach in identifying non-vocalizing specimens. Lower counts in families such as Fringillidae (finches) indicate a lack of adequate resources, such as seeds, in the mangrove habitat. These findings align with studies in tropical mangroves, where bird diversity reflects habitat complexity and resource availability (Buelow & Sheaves, 2015; Nagelkerken et al., 2008). Therefore, our survey's count emphasizes Saco da Inhaca's role as a representative site.

The species accumulation curve (SAC) did not reach a plateau, indicating that the three-day survey captured only a subset of the potential avifauna diversity in Inhaca Island, which is known to host *ca.* 300 bird species, including residents and migrants (de Boer & Bento, 1999). This incomplete asymptote is common in short-term surveys of biodiverse habitats like mangroves, where cryptic or seasonal species may be missed (Marques et al., 2013). The weak positive relationship

between sampling effort and species richness further emphasizes that effort alone does not drive observed diversity, with no spatial patterns detected despite plots with high diversity being adjacent to those with low richness. This lack of spatial clustering suggests microhabitat factors, such as vegetation density, play a more dominant role than broad spatial arrangement, consistent with mangrove bird distribution patterns where patchiness influences community structure (Luther & Greenberg, 2009).

The statistical models employed in our study highlight the challenges of identifying environmental drivers of bird species richness in the Saco da Inhaca mangrove forest, reflecting the complexity of ecological systems. The Generalized Linear Model (GLM) and Generalized Additive Mixed Model (GAMM) showed no significant effects of time of day or sampling effort on species counts, suggesting these factors are less influential than anticipated in shaping avifauna distribution within the short survey period. The GLM's perfect fit likely indicates overfitting due to the small sample size (13 plots) and categorical plot predictors, a common issue in ecological studies where models may capture noise rather than generalizable patterns (Zuur et al., 2009). Similarly, the GAMM's low explanatory power and non-significant smooth terms for hour of day and plot number suggest that unmodeled factors, such as tidal cycles, vegetation composition (e.g., dominance of *Avicennia marina* or *Rhizophora mucronata*), or microhabitat features, likely drive observed richness patterns. The significant spatial autocorrelation in GAMM residuals indicates that sites with similar species counts are spatially clustered, pointing to unaccounted spatial structures like proximity to tidal channels or human settlements (Dormann et al., 2007). These findings suggest that while our models provide a preliminary framework, future studies should incorporate spatial covariates and environmental bottom-up variables, such as salinity or tree density, to better capture the ecological processes influencing bird diversity in mangroves.

Bioacoustic monitoring proved effective in this study, enabling non-invasive species identification and diversity assessment in the dense mangrove environment, where visual surveys are challenging (Marques et al., 2013). The use of mobile phones and Audacity for spectrogram generation, combined with xeno-canto comparisons and BirdNET

v1.0, facilitated the creation of a bird song library, categorizing vocalizations by species. BirdNET's performance, while useful, required manual verification for misclassifications, highlighting its limitations in noisy or complex soundscapes but affirming its value as a supplementary tool. This approach demonstrated scalability and reduced bias compared to traditional methods, though equipment constraints (e.g., mobile phone sensitivity) may have underestimated quiet or distant calls. The integration of direct observations with acoustics enhanced accuracy, capturing both visual and auditory data, but the short duration and morning-only sampling likely missed nocturnal or seasonal species, underscoring the need for extended monitoring.

The observed diversity in Saco da Inhaca reflects the mangrove's health as a functional ecosystem, supporting nutrient cycling and habitat stability through bird activities (Appoo et al., 2024; Lovelock et al., 2004). Dominant families such as Pycnonotidae contribute to insect control and seed dispersal, including those of parasitic plants (Convolvulaceae) observed on some mangrove trees, thereby adding another interesting dimension to the ecological interactions. Bird dispersal of parasitic plants in mangroves is ecologically important because it directly connects avian communities with host–parasite interactions, with cascading effects on forest structure and biodiversity (Reid, 1991; Watson, 2001). On the other hand, the presence of sunbirds (Nectariniidae) highlights their potential role as pollinators of mangrove trees, a function only briefly reported by Davey (1975). These findings highlight the need to promote dedicated research on these underexplored ecological dynamics in the study area.

According to de Boer & Bento (1999), the bird community on Inhaca Island does not reflect the composition of the average Mozambican avian community, where 78% of species are resident, compared to only 40% on Inhaca. This underscores the island's importance as a refuge for Palearctic and intra-African migrants, as well as for rare vagrants. Our findings highlight the need to establish monitoring programs that integrate bioacoustics to track changes in bird communities in response to climate change, increasing tourism, and pollution.

Limitations of the study include the short three-day duration, restricting sampling to morning hours and potentially missing diurnal

variations or seasonal migrations. The use of mobile phones, while accessible, limited recording quality, possibly underestimating diversity. Sampling design issues, such as variable recordings per plot, may have introduced bias, and the small sample size (13 plots) contributed to model overfitting. Future directions should extend sampling periods and seasons, incorporate professional microphones and passive recorders for 24-hour data, and integrate visual methods like camera traps for validation. Comparing avifauna to mangrove features (e.g., biomass, carbon stock) could provide deeper insights. Community engagement through citizen science apps like BirdNET could enhance data collection and awareness, supporting sustainable tourism and protection in Inhaca.

VI. Conclusion

The avian population in Saco Bay of Inhaca shows the potential of the region's ecological richness. Protecting these habitats is crucial for maintaining biodiversity and supporting resident and migratory bird populations. Engaging local communities in conservation efforts and promoting sustainable tourism can further enhance the preservation of this unique ecosystem. Instruments such as mobile phones and free applications, even if not accurate, could increase engagement from local people and improve awareness towards wild species protection. In particular, we noticed a significant improvement in BirdNet identification rate, which would make this kind of preliminary surveys more affordable and widespread.

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Appendix A. Taxonomic composition and abundance of bird species recorded in the mangroves of Saco Bay, Inhaca Island.

Order	Family	Species	No. of individuals
Cuculiformes	Cuculidae	*Centropus superciliosus*	2
Columbiformes	Columbidae	*Turtur chalcospilos*	2
		Streptopelia capicola	2
Charadriiformes	Recurvirostridae	*Recurvirostra avosetta*	1
	Scolopacidae	*Numenius phaeopus*	5
	Laridae	*Larus fuscus*	5
Pelecaniformes	Threskiornithidae	*Bostrychia hagedash*	1
	Ardeidae	*Ardea alba*	1
Accipitriformes	Pandionidae	*Pandion haliaetus*	1
Bucerotiformes	Bucerotidae	*Bycanister buccinator*	1
Coraciiformes	Alcedinidae	*Ispidina picta*	3
Piciformes	Lybiidae	*Pogoniulus bilineatus*	3
Passeriformes	Sturnidae	*Acridotheres tristis*	1
	Cisticolidae	*Apalis flavida*	1
		Camaroptera brachyura	1
		Cisticola chiniana	2
	Pycnonotidae	*Andropadus importunus*	24
		Pycnonotus barbatus	3
	Phylloscopidae	*Phylloscopus ruficapilla*	1
	Muscicapidae	*Muscicapa striata*	2
	Nectariniidae	*Chalcomitra senegalensis*	5
		Hedydipna collaris	1
		Cinnyris bifasciatus	3

	Passeridae	*Passer domesticus*	2
	Fringillidae	*Crithagra sulphurata*	1

A brief overview of the morphological and taxonomic diversity of birds found in the mangroves of Inhaca. Although there is a clear predominance of species associated with the aquatic environment, purely terrestrial species can also be found, which feed and even reproduce in these forests. (photos Paolo Ramoni-Perazzi).

THE COMPONENT 2 - PROJECT MANGROWTH
PRESERVATION OF ECOSYSTEMS FOR SUSTAINABLE DEVELOPMENT

In Mozambique's coastal landscapes, mangroves stand as vital ecosystems, supporting biodiversity and sustaining the livelihoods of coastal communities. However, these forests face increasing pressures, both natural, such as cyclones, and anthropogenic, including saltpan expansion, logging, and urban development. As a result, the well-being of the 60 percent of the coastal population that depends directly on mangrove services has been placed at risk, making urgent conservation action indispensable.

It is within this context that the ManGrowth Project was created, particularly Component 2, which is dedicated to strengthening the scientific capacity of the Inhaca Marine Biology Station (EBMI), Eduardo Mondlane University (UEM). Since its inception, the project has not only achieved its original objectives but has, in fact, surpassed them in several important way.

In addition to these training opportunities, the project has contributed directly to academic progress. Two undergraduate theses and one master's dissertation have already been completed in the framework of ManGrowth, with several more currently underway. At the same time, a growing number of scientific papers have been published on different aspects of mangrove ecology and conservation, while other manuscripts are in preparation for submission. These outputs illustrate how the project has generated tangible contributions to scientific knowledge that go beyond its original scope.

One of the clearest achievements has been the complete recuperation of the EBMI dormitories, which have been fully repaired, furnished, and equipped to ensure that both students and researchers can enjoy a comfortable stay while working at the station. At the same time, the project has overseen the final stages of construction of the protective wall surrounding the new laboratory, further consolidating the infrastructure necessary for advanced marine and coastal research.

Training and capacity building have also been central pillars of the project. So far, more than 114 students have taken part in *Summer Schools* or intensive courses covering a wide range of themes at the postgraduate level. The latter activities are formally recognized by the Master's in Biology and Conservation Ecology of UEM, thus ensuring that the knowledge and skills acquired are embedded in the country's academic system. Several of the studies developed during the *Summer Schools* have subsequently been presented at national or international conferences, demonstrating the quality and visibility of the work carried out.

Taken together, these achievements confirm that the ManGrowth Project has gone far beyond the expectations set at its outset. It has strengthened scientific capacity, modernized infrastructure, expanded research opportunities, and trained a new generation of conservation scientists. Above all, it has created the foundations for a sustainable future in which mangroves are not only protected but studied, understood, and managed as living systems essential to both ecosystems and communities. The steps already taken indicate a deep commitment to preserving these vital coastal forests and ensuring that they continue to thrive for generations to come.

The harder you work, the prouder you are of what you achieve: Some students proudly display the certificates they earned during the 2024 Summer School. Although the unrest in Maputo prevented all participants from attending in person, everyone was united in spirit (photo Enrico Nicosia).

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